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THE TEMPERATURE OF THE ARC.[1]

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THE comparison of the methods of extrapolation that must be resorted to in the estimation of extremely high temperatures is of growing importance in establishing a satisfactory tentative scale of temperature which is already required in many scientific and industrial operations.

In a study of the possibilities of the application of optical and radiation methods of pyrometry to the estimation of extremely high temperatures we have been led to compare a number of carefully calibrated optical pyrometers at the "temperature of the arc."

The early attemps to estimate the so-called temperature of the arc, or more precisely the temperature of the hottest portion of the positive crater were based on the extrapolation of empirical relations connecting radiation and temperature (Newton, Dulong and Petit, Rosetti, etc.), that were only applicable through very narrow ranges of temperature and the results to which they have led are now only of historical interest.

The first important measurement was that of LeChatelier,[2] who determined for a number of bodies the relation between the photometric intensity of the red light emitted and the temperature. The photometric measurements were made with his optical pyrometer and the temperature measurements with the now well-known LeChatelier thermocouple (platinum, platinum-rhodium 10 per cent.).

[1] Communication from the National Bureau of Standards.

[2] LeChatelier, C. R., 114, p. 737, 1892; Jl. de Phys. (3), 1, 185, 1892.

This empirical relation is based on experiments extending over the range 700° C. to nearly 1800° C. LeChatelier found by the extrapolation of this relation ($I = 10^{6.7} T^{-3210/T}$) for the temperature of the arc 4400° abs. The red light was obtained by passing the radiation through red glass which probably lets through the shorter wave-lengths at high temperatures so that the measured intensity would increase more rapidly than the formula would indicate. This would act in the direction of making the result come out too high.

Violle[1] made an estimate of the temperature of the arc by a calorimetric method. A small removable button of carbon on the end of the positive crater was dropped into the calorimeter. The specific heat of carbon was measured and found to obey a linear relation for a considerable range above 1,000°, and the relation thus established was assumed to hold as far as the temperature of the arc. The final value found by Violle was given as 3875° abs. Among the great experimental difficulties of this method are those due to loss of heat by the button in falling to the calorimeter and to non-uniformity of heating. Violle investigated these by varying the height of fall and size of the button. In general criticism of this method it should be noted that the specific heat of most substances increases more rapidly as the temperature corresponding to change of state is approached than at low temperatures. Although the difficulties of this method are very great, as admitted by Violle, the result is nevertheless interesting as a determination by a method widely different from those usually employed based on the extrapolation of relations connecting radiation and temperature.

Wilson and Gray[2] made an estimate of the temperature of the arc by a method in which the radiation from the positive crater falling on one junction of a differential radiomicrometer was balanced by the radiation on the other junction from a known area of incandescent polished platinum strip, whose temperature was measured by its expansion after the principle of the Joly meldometer. The relation between the radiation of polished platinum and of platinum covered with copper oxide was then determined and the

[1] Violle, C. R., 95, 1273; Jl. de Phys. (3), 2, 545, 1893; C. R., 120, 868, 1895.

[2] Wilson and Gray, Proc. Roy. Soc., 58, 24, 1895; Phil. Trans., A, 185, 361, 1894, for the details of apparatus, same as used in estimation of temperature of the sun.

assumption made that the radiation from the carbon obeyed the same law as from the copper oxide, which is very nearly the case. Knowing then the apparent areas of the two sources of radiation, and knowing the relation connecting radiation and temperature, they could at once find the temperature to which the platinum strip would have to be raised to balance the arc if the apparent areas were equal. The result to which these experimenters were led was 3600° absolute. In discussing this experiment which was admirably carried out it must be remembered that it was done at a time when the laws of radiation were not so well understood as they were a few years later. The method of measuring the temperature made use of in these experiments is capable of considerable precision. Their temperature scale is probably about 20° low at 1000°, inasmuch as the melting point of gold was taken as 1041° in the calibration of the platinum strip. The radiation of the bare platinum was found to increase approximately as the 4th power of the absolute temperature and of the blackened platinum about as the 3.4th power. This is not in agreement with subsequent researches of Paschen and of Lummer, Pringsheim and Kurlbaum. The bare platinum was enclosed in a gilt case, which made it approximate more or less to a black body. The strongest criticism of this method is undoubtedly that it is based on the extrapolation of an empirical relation which was studied only through a comparatively narrow range of temperature (650° to 1150°), and the results cannot, therefore, be given so much weight as those obtained by the extrapolation of Planck's law, which has been found to satisfy the results of experiment throughout the range from — 200° C. to + 1500° C.

Wanner[1] studied experimentally the relation connecting the temperature and the photometric intensity of monochromatic light of different wave-lengths emitted by several black bodies of different construction, up to about 1400° absolute, and found that the results were in agreement with Wien's relation for the spectral distribution of energy for a black body, $J = c_1 \lambda^{-5} e^{-c_2/\lambda T}$, as shown by the linear relation between $\log J$ and $1/T$. Wanner then applied this method to an estimation of the temperature of the arc, by comparing with

[1] Wanner, Ann. d. Physik, 2, 141, 1900.

a spectrophotometer the intensity of the red ($\lambda = 0.6563\mu$) and green ($\lambda = 0.5461\ \mu$) radation with the intensity of the same radiation emitted by a black body (indirectly for convenience through the intermediary of an amylacetate flame whose radiation for these wave-lengths had been compared with black body radiation). Using red light Wanner finds for the temperature of the hottest portion of the positive crater 3720°, and using green light 3700° abs. when cored carbons (Dochtkohle) are used; using retort carbons he finds for measurements with the red and green light 3875° and 3895° abs. respectively. If it can be assumed that the Wien equation continues to hold for such extremely high temperatures, which will be referred to again, this determination of Wanner must be given considerable weight, as the method is capable of precision. It must be noted that inasmuch as this determination is based on the extrapolation of the Wien equation which applies to a black body, the temperature thus found is the "black body temperature," *i. e.*, the temperature that a black body would have to emit light of the same intensity. Barring the presence of luminescence, this method therefore gives the lower limit of temperature, so that the true temperature of the positive crater must at least be higher, by an amount depending on how much its radiation differs from black body radiation.

Lummer and Pringsheim[1] made use of the relation $\lambda_m T = \text{const.}$ connecting the wave-length λ_m having maximum energy and the absolute temperature T of the radiating body, to estimate the limiting temperatures of a number of incandescent bodies, such as the Nernst filament, the Welsbach mantle, Argand gas flame, and the electric arc. The value of the constant for a black body is 2940 according to their experiments and 2921 by those of Paschen,[2] a most satisfactory agreement. For the radiation from polished platinum Lummer and Pringsheim have found for the constant 2630. Assuming then that the "displacement law" continues to hold, and that the radiation from the crater of the arc is of the same character as from the black body and platinum, and is

[1] Lummer and Pringsheim, Verhandl. d. Deutsch. Phys. Ges., I., 235, 1899; III., 36, 1901.

[2] Paschen, Ann. d. Phys., 4, 277, 1901.

intermediate between these, which they have shown is very probable, these investigators concluded that the temperature of the positive crater must be between

$$T_{\min} = \frac{2630}{0.7} = 3750^\circ \text{ and } T_{\max} = \frac{2940}{0.7} = 4200^\circ \text{ abs.}$$

From the flattened form of the energy curve and the effect of atmospheric absorption, it is difficult to locate the position of the maximum with precision. It must be said that the "displacement law" on which this method is based is one of the best established laws of radiation, both from the theoretical and experimental side.

Petavel[1] has found that his observations on platinum radiation satisfy the formula

$$(t - 400) = 889.6 \sqrt[6.9]{b}$$

where t is degrees centigrade and b the intrinsic brilliancy per square centimeter measured photometrically. For the crater of the arc he found $b = 11{,}000$ candles per cm.^{2}, which would give $t = 3830^\circ$ C. (4100° abs.) assuming that carbon and platinum obey the same radiation law. This assumption gives too high a value for t. With the constants proper to carbon in the above formula, the method might give good results.

By an examination of a spectral energy curve of the positive pole of an electric arc in a paper by Abney and Festing,[2] F. W. Very[3] was led to fix the maximum at about $0.73\,\mu$. This gives for the upper and lower limits between which the temperature of the positive carbon must lie

$$T_{\max} = \frac{2940}{0.73} = 4025^\circ \text{ abs.}$$

$$T_{\min} = \frac{2630}{0.73} = 3600^\circ \text{ abs.}$$

More recently, Féry[4] has made estimates of this temperature by two different methods. In one the radiation from the positive carbon was focused by a fluorite lens on the blackened junction of

[1] Petavel, Phil. Trans. Roy. Soc., **191**, 501, 1898.
[2] Abney and Festing, Proc. Roy. Soc., **35**, p. 334, diagram II., 1883.
[3] F. W. Very, Astrophysical Journal, **10**, p. 208, 1899.
[4] Féry, C. R., **134**, 977, 1201, 1902.

a minute iron-constantan thermocouple which was joined in circuit with a galvanometer. A preliminary calibration of this thermo-electric telescope with the radiation from an electrically heated black body as far as 1500° C. showed that the observed deflections of the galvanometer were in most satisfactory agreement with those calculated from the Stefan-Boltzmann law. By this method Féry was led to the value 3763° abs. as the "black body temperature" of the arc. In this connection it is of interest to note that Lummer and Kurlbaum[1] have found that while the energy of total radiation from iron oxide, which is very approximately the same as from carbon, is only 30 per cent. of that from a black body at 654° abs.; at 1481° abs. it has already grown to 60 per cent. This would indicate that the "black body temperature" of the arc as found by the energy of total radiation from carbon would not differ very much from its true temperature, probably by less than 200°.

Using the photometric method and a modified form of the LeChatelier optical pyrometer and assuming that Wien's law continues to hold, Féry finds 4140° abs. with red light and 4170° abs. using green light. As an explanation of this high value, want of monochromatism of the glass used at once suggests itself. The explanation certainly applies for the usual red glasses that are sent out by Pellin with the LeChatelier optical pyrometer. Moreover, the "center of light" transmission of this glass is nearer to 0.631 μ than 0.659 μ, the value usually assumed from LeChatelier's early determinations, probably made with a different kind of glass.

EXPERIMENTAL RESULTS.

The methods we have used are all dependent on the extrapolation of Wien's equation for the distribution of energy in the spectrum of a black body,

$$J = c\lambda^{-5}e^{-c_2/\lambda T}.$$

The researches of Lummer and Pringsheim,[2] Paschen,[3] Rubens

[1] Lummer and Kurlbaum, Verh. phys. Ges., Berlin, 17, 106, 1898.

[2] Lummer and Pringheim, Verh. d. Deutsch. Phys. Ges., 1, 23, 215, 1899; 2, 163, 1899; 3, 6, 1901. Lummer, Sur le rayonnement des corps noirs, Int. Cong. Rap., Paris, 1900.

[3] Paschen, Ann. d. Phys., 4, 277, 1900.

and Kurlbaum,[1] and Beckmann[2] have shown that this law does not hold for long wave-lengths and high temperatures. The results of experiment are better represented by the equation deduced by Plank,[3]

The experiments of Rubens and Kurlbaum have shown that this equation is in most satisfactory agreement with the results of experiment throughout the widest range of measurable temperatures, $-200°$ C. to $+1500°$ C., and for the longest waves of the infra-red portion of the spectrum obtained by multiple reflection from fluorite ($\lambda = 24.0\mu$ and 31.6μ) and rock salt ($\lambda = 51.2\mu$) surfaces.

However, for the wave-lengths of the visible spectrum, and even for the region of the infra-red in which the largest part of the total energy of the spectrum is found, Wien's law applies with sufficient precision. Lummer and Pringsheim have shown that for values of λT less than 3000, Wien's equation represents the results of experiment to an order of accuracy of 1 per cent. For the photometric measurements in the visible spectrum where the wave-length does not exceed $0.65\,\mu$, the use of Wien's equation is justified for extrapolation to temperatures exceeding 4000° C.

We have determined the temperature of the brightest portion of the positive crater of the electric arc by means of the three pyrometers devised respectively by Le Chatelier, Wanner and Holborn-Kurlbaum. The three instruments are photometers. In the Wanner a narrow spectral band in the red is used as monochromatic source, while in the other two dependence has to be placed upon colored glasses for monochromatism. In the Holborn-Kurlbaum[4] pyrometer, the tip of a very fine incandescent lamp filament is made to disappear against the bright background observed, by varying the current through the lamp. The current is then a function of the temperature which may be found by calibration against a thermocouple.

[1] Rubens and Kurlbaum, Sitzungsber. der k. Akad. Berlin, **41**, 929, 1900; Ann. d. Phys., **4**, 649, 1900.

[2] H. Beckmann, Inaug. Dissert. Tübingen, 1898.

[3] Planck, Verh. d. Deutsch. Phys. Ges., **2**, 202, 237, 1900; Ann. d. Phys., **4**, 553, 1901.

$$J = c_1 \frac{\lambda^{-5}}{e^{\;\;} - 1}.$$

[4] Holborn and Kurlbaum, Ann. der Phys., **10**, 225, 1902.

In the Wanner[1] instrument a polarizing device permits balancing photometrically the intensities of the same spectral hues coming from a standard light and the source observed. The angle of the analyzer may be converted into degrees of temperature by calibration. In the LeChatelier[2] instrument the light from the source is cut down by a cats-eye diaphragm until photometric equality is had with light from a comparison source, when from the opening of the cats-eye the temperature may be calculated after the instrument has been calibrated.

Between such a bright source as the arc and any of these instruments it is necessary in order to render photometric comparison possible, to interpose absorbing glasses whose absorption factors (K) have to be determined for the different wave-lengths used.

Wien's law gives:

$$(1) \qquad \log_{10} K = \log \frac{J_1}{J_2} = \frac{c_2}{\lambda} \log_{10} e \left(\frac{1}{T_2} - \frac{1}{T_1} \right),$$

where $c_2 = 14{,}500$ for a black body, where λ is expressed in μ, e is the base of Naperian logarithms, J_1 and J_2 are the light intensities expressed in any units corresponding to the temperatures T_1 and T_2, T_1 being the absolute black body temperature of the source and T_2 its apparent temperature when the absorbing glasses are interposed. This formula may be used with any of the above pyrometers to determine the arc temperature when K is known and the reading of each instrument has been found for some source which can be viewed without the absorption glasses. As a convenient reference temperature, or source of constant intensity, that of the central area of a definite acetylene flame viewed normally was used. The apparent black body temperature of this source was 1625° abs., the different instruments agreeing to within 3° in this determination. Each of the instruments was also calibrated over a considerable temperature range in terms of a thermocouple using a Lummer-Kurlbaum black body as source, thus obtaining a whole series of comparison points. The two methods gave concordant results.

The values of absorption factors (K) vary with the wave-lengths of the light used; K decreasing quite rapidly for shorter wave-

[1] Wanner, Phys. Z. S., 3, 112, 1902.

[2] LeChatelier, Jl. de Phys. (3), 1, 185, 1892.

lengths. Thus a given absorbing glass gave $K = 1500$ for $\lambda = 0.651\ \mu$ and only 360 for $\lambda = 0.550\ \mu$. Also with these glasses the value of K for n glasses is not K^n, as is generally assumed, but something less than this quantity. Four glasses of the same quality and thickness gave, for $\lambda = 0.651\ \mu$, the following results as determined from a large number of observations using all three pyrometers in this determination :

No. of Glasses.	1	2	3	4
Value of K.	11.9	137	1500	15500
Increment of K.	11.9	11.5	10.9	10.3

The results of our determination of the arc temperature for a current of fifteen amperes are given in the three following tables. The carbons were exceptionally homogeneous, prepared especially for optical projections and arcing very readily ; the positive carbon (13 mm. diameter) being mounted horizontally and the negative (11 mm. diameter) being vertical. The potential across the arc was about 65 volts. In order to prevent the formation of a deep crater on the under side of the positive carbon the latter was occasionally trimmed down so that the hottest part of the crater could be readily viewed in a horizontal line.

Although the three pyrometers give practically an identical value (3700° abs.) for the arc temperature, yet we do not consider all the observations of equal weight. The red glass $\lambda = 0.630\ \mu$ is not sufficiently homogeneous for good photometric measurements ; with the Holborn-Kurlbaum instrument, for instance, the filament of the lamp cannot be made to disappear when using this glass. Glass $\lambda = 0.651\ \mu$, on the other hand, leaves practically nothing to be desired as to its homogeneity and the results obtained with it have the greatest certainty. The values of the equivalent wave-lengths for the red glasses were verified by Dr. Nutting to an accuracy well within the limits of error from other sources.

The relative temperatures obtained with the various instruments are independent of the absorption factors, the latter being dependent upon the absorption glasses, which were the same for all the pyrometers, and upon the wave-length used. The absolute values we have obtained for the arc temperatures would evidently be in

Determinations with Holborn-Kurlbaum Pyrometer.

Date, 1904.	Number of Lamp used in *H-K* Pyrometer	Wave-length trans. by Glass.	*K* = Absorption Factor.	Absolute Temperature of Arc.
June 14.	No. 132	0.651 μ	1500	3670
" "	156	"	"	3680
" "	145	"	"	3680
" 15.	132	"	"	3630
" "	156	"	"	3690
" "	145	"	"	3670
" 20.	132	0.630	1350	3750
" 15.	156	"	"	3790
" 16.	132	0.550	360	3640
				Mean, 3690

Determinations with LeChatelier Optical Pyrometer.

Date.	Wave-length Used.	*K* = Absorption Factor.	Absolute Temperature of Arc.
June 17.	0.651 μ	15500	3740
" "	"	"	3750
" "	"	"	3750
" "	"	"	3690
" 16.	"	1500	3730
" 18.	0.630	14850	3680
" "	"	1350	3730
			Mean, 3720

Determinations with Wanner Pyrometer.

Date, 1904.	Wave-length Used.	*K* = Absorption Factor.	Absolute Temperature of Arc.
June 20.	0.656 μ	1500	3660
"	"	"	3700
			Mean, 3680

error if the absorption coefficients are incorrect. The values chosen are the best that could be deduced from several hundred observations made with all the pyrometers. The absorption factor for green light ($\lambda = 0.550\,\mu$) is however less well determined.

As to the pyrometers themselves and the reliance to be placed upon the results obtained with the different instruments, the greatest uncertainty seems to be with the Wanner because it is more diffi-

cult with this instrument than with the others to be sure that one is sighting upon the desired spot, as the instrument is not a telescope; also the extrapolation of the scale of this particular instrument is somewhat uncertain. As between the LeChatelier and Holborn-Kurlbaum determinations, the preference is in favor of the latter, as a smaller area is used in the photometry and there are more independent checks upon its calibration; thus using three comparison lamps, identical results are obtained.

On the whole, a better agreement among different instruments employing such varied methods of measurement could hardly be expected at such a high temperature. Our experiments with pure graphite have shown that the value, 3700° abs., would not be increased by more than 50°. The effect of material of carbons and of current density will also be considered.

Variations in Temperature of the Arc.

(*a*) *With Current.* — It is generally accepted since Violle[1] so stated, that the temperature of the arc is independent of the current and this temperature is assumed to be the boiling point of carbon. There are, however, at least, two reasons for which we should expect this temperature to vary with the current. As the current is increased there will be a tendency to superheat the viscous carbon layer from which the vapor boils, even though this vapor does not have a higher temperature than the normal boiling point, and as it is this viscous layer which is observed, variations of current above a certain limit should be accompanied by changes in temperature. Again, with low current a smaller area is heated so that it will be more cooled by conduction.

An examination of the observations from which it has been inferred that the arc temperature is independent of current seems to indicate that this conclusion is unwarranted, for no observer has published a series of results sufficiently concordant in themselves or of sufficient number to enable him to state with certainty whether or not the effect exists. This has been due largely to the tediousness or inadequacy of the methods employed.

The constancy of brightness was first announced as probable by

[1] Violle, Jour. de Phys. (3), **2**, 545, 1893.

Rossetti in 1878, and Violle was the first to state as a result of his own experiments that "the brightness of the positive carbon is rigorously independent of the electric power expended to produce the arc," changing from within the limits 10 amperes at 500 watts to 400 amperes at 34,000 watts. Carbons of 3.5 cm. diameter were used for the high currents, but no details of observations are published nor the precision of his spectrophotometric method, which is certainly sensitive though it would be expected that any effect for very high currents would be neutralized in part at least by the larger carbons used. Furthermore, results with carbons of varying size and quality are not comparable. Although Violle showed undoubtedly that with carbons of different sizes adapted to carrying currents of from 10 to 400 amperes, there is no considerable change in temperature, yet it would seem that he did not show conclusively that for a given sized carbon there is no variation of temperature with current for the brightest portion of the positive crater.

Wilson & Gray found that changing from 14 to 25 amperes "the temperature then appeared to be a little higher than with the smaller current. . . . Later experiments . . . indicate an exact equality of temperature." They do not give any data, but their published observations on the arc temperature indicate that it would be difficult to detect variations by their method.

Wanner states that "changing the current 1½ times (15 to 22 amperes) remains without influence." Wanner's published results for a given kind of carbon are few in number (four) and vary over ninety degrees under the same conditions, so that any difference due to current changes might be masked.

Our experiments on the variation of arc temperature with current were first made with a Holborn-Kurlbaum pryometer which is peculiarly well adapted for these measurements, as it is readily sighted and thus the wandering of the brightest spot on the crater can be easily followed; a very small photometric area is employed; and observations may be taken rapidly, within intervals of a few seconds.

In order to secure a good sized image of the crater so as to facilitate the photometric measurements, the instrument, provided

with auxiliary lenses and suitable absorption glasses, was placed as near as possible (12–25 cm.) to the arc, which was mounted as previously described. The current from a 120-volt storage battery was varied without the observer being aware of the actual changes, and to render the settings of the pyrometer as unbiased as possible an additional rheostat in its lamp circuit was also worked independently of the observer. No observations were taken on a hissing or humming arc, nor until the arc burned normally after changing current, and the conditions of constant length of arc and constant P.D. across the arc were very closely maintained, the latter being measured with a Weston voltmeter; the value of the P.D. was about 65 volts. Two observers obtained practically identical results which are here summarized:

Date.	Number of Observations.	Current in Arc (Amperes).	Temperature of Arc (Absolute).
June 23, 1904.	51	15	3690
	48	22	3727
	49	30	3782
June 28, 1904.	23	15	3690
	37	22	3741
	42	30	3762

A few observations were also taken with a current of 40 amperes which indicated that the effect persists with increasing current density to the limit that the auxiliary apparatus would stand.

The precision with which this determination can be made on a single carbon with the Holborn-Kurlbaum instrument is shown by the observations of June 23, 1904, namely, that the probable error of the mean in any one of the three series on that date is less than 3° and no photometric observation with a current of 15 amperes was as high as the mean value for 30 amperes. Whatever may be the best value for the arc temperature, this value is apparently a function of the current when the P.D. across the arc is a constant and the arc is burning normally.

If the current is kept constant and the P.D. varied it is necessary to vary simultaneously the length of the arc, therefore temperature results obtained by this method of varying the power are not

directly comparable as the length of the arc is a variable not easily eliminated quantitatively.

It does not seem that our finding a small temperature change with current can be explained on physiological grounds, due to contrast in light intensities entering the eye, since with the smallest current used the image of the hottest part of the crater was many times larger than the image of the filament of the comparison lamp. To further test this point we determined the difference in temperature with a LeChatelier optical pyrometer provided with auxiliary lens and a very homogeneous red glass before the eyepiece. A number of consistent observations indicate that changing the current from 15 to 30 amperes causes a rise in temperature of about 70°. With this instrument the eye does not receive light except through a 1 mm². opening, so that the effects of the surrounding field cannot influence the eye.

(*b*) *With the Material of Carbons.* — Wanner finds a difference of about 170° in changing from cored to retort carbon, the former giving a low value, and our experiments also show that the kind of carbon used will influence the apparent temperature of the arc. The homogeneous carbons described above gave us results 40° lower than with a very pure graphite furnished by the Acheson Company. This result was obtained both with the Holborn-Kurlbaum and LeChatelier optical pyrometers.

In commercial carbons, the presence of salts seems to facilitate the arcing, and with large currents a steadiness can be had which cannot be approached with pure graphite carbons. It appears that the arc temperature as determined with commercial carbons is lower than the point obtained for pure carbon.

(*c*) *Effect on the Arc as a Standard of Light.* — These questions are of interest in connection with the proposed use of the radiation from a definite area of the brightest part of the crater of the + carbon of the electric arc as a standard source of light.. If the variations in temperature are as great as indicated in our experiments a variation of current from 15 to 22 amperes (corresponding to a temperature variation of 40° C. in the temperature of the arc) would correspond to a variation in the photometric intensity of something like 7 per cent. Even with the same current and the same

carbons our results appear to show relative time changes of photometric intensity that seem considerably greater than the experimental errors, that may be due to varying shape of the carbons and changes in current density, as well as variations in the composition of the material. While it would be possible to define the current, it would not be as easy to control the form of the crater and the current density in the region from which the light is to be taken.

Another difficulty in the above method of defining a light standard arises from the variations that may result from the use of different kinds of carbon as shown above. The experiments of Wanner indicate an enormous change in the intensity of light due to this cause.

Blondel[1] recognized the objections to the use of a screened area of the positive crater as a primary standard of light and recommended its use as a secondary standard for arc photometry. He found the nature of the carbon to be important in determining the absolute brightness (of a square millimeter); thus for five different qualities of homogeneous carbon an average value of 158 candles was found, the extremes being 150 and 163. With cored carbons he obtained values lower than 130 candles for the maximum brightness.

Conclusion.

A résumé of the estimates of the arc temperature that have been discussed in the preceeding pages is given in the table.

From this table it will be seen that the photometric methods based on the extrapolation of Wien's equation show that the "black body temperature of the arc" (pure graphite) is at least 3750° abs. so that its true temperature must be higher than this; it is not possible to state how much, in the absence of more definite knowledge concerning the departure of carbon from black body radiation. In the light of the best evidence that is at present available it would seem that the true temperature of the hottest part of the positive carbon is between 3900° and 4000° absolute.

If we are justified in assuming that the high values found by LeChatelier and by Féry, using photometric methods, are satisfactorily explained by the reasons we have advanced, a comparison of the results contained in the above table will show, when we consider

[1] Blondel, Proc. Int. Elec. Congress, Chicago, 1893.

Observer.	Absolute Temperature of the Arc.	Method.
LeChatelier.	4370	Photometric: Intensity of red light.
Violle.	3870	Calorimetric: Specific hest of carbon.
Wilson & Gray.	3600	Total radiation of copper oxide, empirical relation for.
Wanner.	3700–3900[1]	(Varying with carbons used.) Photometric, in terms of Wien's law.
Very.	Between 3600 and 4000	Wave-length of maximum energy Wien's displacement law: $\lambda_m T = C$.
Lummer and Pringsheim.	Between 3750 and 4200	Wave-length of maximum energy Wien's displacement law: $\lambda T = C$.
Féry.	3760[1]	Total radiation: Stefan-Boltzmann law.
	4150[1]	Photometric: Wien's law.
Waidner & Burgess. (2)	3690[1]	Holborn-Kurlbaum Pyrometer, Wien's law.
	3680[1]	Wanner Pyrometer, Wien's law.
	3720[1]	LeChatelier Pyrometer, Wien's law.

the experimental difficulties and uncertainties that may enter due to varying conditions of the arc (such as current strength, length of arc, quality of carbon, etc.), that the results obtained, dependent as they are on the extreme extrapolation of different laws, are in quite satisfactory agreement, and diminish somewhat the doubt which is always present when we must venture beyond the domain of experiment.

The value obtained by Féry for the "black body temperature" of the arc, by making use of the Stefan-Boltmann law for the total radiation of a black body, is in most satisfactory agreement with the results obtained by Wanner, dependent on the extrapolation of the Wien-Planck relation, and is nearly identical with our own photometric determinations, based on the same relation. It is interesting to note in this connection that Lummer and Pringsheim[3] have found these laws in agreement at 2300° abs.

[1] Black body temperature.

[2] Pure graphite gives a temperature not over 50° higher.

[3] Lummer and Pringsheim, Verh. Deutsch Phys. Ges. (5), 1, 3, 1903.

If we can assume that the Wien-Planck and the Stefan-Boltzmann relations continue to hold good for thermodynamic radiation at these high temperatures, it would seem, in view of the above facts, that the phenomena of luminescence plays no very important part in the radiation from the positive pole of the electric arc, for, if so, it might be expected to lead to higher values in the estimates based on the photometric methods than would be found by methods dependent on total radiation.

An examination of the available estimates of the temperature of the sun made by methods based on the photometric intensity seems to indicate that these methods lead to higher values than those based on the energy of total radiation. Thus, using the former method LeChatelier[1] finds 7900°[2] abs. The estimates[3] based on total radiation and on the position of the wave-length of maximum energy in the solor spectrum lead to values in the neighborhood of 5500° to 6000° absolute. If this difference in the methods really exists, it would at least suggest the presence of luminescent radiation. It would also be of interest in this connection to use the photometric method with green and blue in addition to red radiation, to see if the former led to higher values as might be expected if luminescence played an important rôle.

[1] LeChatelier, C. R., 114, 737, 1892.

[2] As LaChatelier's determination of the arc temperature is probably several hundred degrees high, his value of the effective temperature of the sun should be lowered.

[3] Day and Van Ostrand, Astrophys. Jl., 19, p. 39, 1904.

(Contribution from the Cryogenic Laboratory of Wesleyan University.)

EFFECT OF MECHANICAL VIBRATION UPON CARBON DIOXIDE NEAR THE CRITICAL TEMPERATURE.[1] I.

BY W. P. BRADLEY, A. W. BROWNE AND C. F. HALE.

NEARLY three years ago, two of the writers undertook a review of some of the ordinary phenomena of the critical state. The apparatus used was of the Cailletet type, and carbon dioxide was chosen as the subject of the experiments. Since no considerable accuracy was required for the object in view, the apparatus was not mounted upon a pier, but upon an ordinary wooden laboratory desk. This fact led to a peculiar observation.

It happened one day that a small wrench in use about the apparatus fell and struck rather sharply upon the desk. At the same instant a bright flash of fog appeared for a moment in the pressure tube. The tube contained at the time both liquid and gaseous carbon dioxide, and the fog was noticed in both phases. The temperature of the bath was about 30°.

Further investigation showed that almost any form of tapping, as with the knuckles, either upon the desk near the apparatus or upon various portions of the apparatus itself, could be employed to produce the effect, and that the density of the fog was clearly dependent upon the violence of the shock thus imparted.

An investigation of the phenomenon was immediately undertaken, which continued with many interruptions and delays for two years or more. The results thus obtained are far from being exhaustive, but are published at this time for the reason that the pressure of other duties prevents a continuation of the inquiry, for the present at least.

There never was any doubt that the appearance of the fog was due to a change in the physical state of the carbon dioxide. Ob-

[1] These studies have been supported by the proceeds of Grant No. 104 from the Elizabeth Thompson Science Fund.

viously the first problem calling for attention was the connection between the blow delivered outside the apparatus and this change of physical state.

To set the problem in better perspective it may be remarked that the appearance of fog in substances which are near their critical state is by no means new or uncommon. So far as we can ascertain, however, it has never been observed under such conditions as have suggested mechanical shock as the cause of it. It usually results from thermal changes in the bath.

Quite independently of the critical state fog can be obtained by expansion in almost any gas or vapor, provided the expansion be of suitable proportions and rapidity. This fact was demonstrated in 1877 by Cailletet in his classical researches upon the liquefaction of the so-called permanent gases. The production of fog in this manner is due to the sudden fall of temperature resulting from the expansion. This leads to the condensation of a multitude of minute liquid droplets, which remain temporarily suspended in the vapor. As the fall of temperature is most pronounced in the center of the tube where the expansion is most nearly adiabatic, the fog is densest in that region. It is always transient, owing to the inflow of heat through the walls of the tube. It may be made to disappear instantly by suddenly restoring the original volume of the system.

Fog may be produced in the liquid phase also by suddenly increasing the volume of the system. In this case, however, it is not due to any change of temperature caused by the expansion, but to the temporary decrease in the pressure to which it was subjected. Multitudes of minute gas bubbles are formed throughout the liquid, rendering it more or less opaque. If the volume of the system undergoes no further change, these bubbles do not disappear quickly like the liquid droplets just mentioned, but remain and rise more or less rapidly and break at the meniscus. They may be made to disappear as suddenly as they came by restoring the original volume. A connection will presently appear between these facts and those which were noticed in our experiments.

To return now to the fog produced by mechanical shock, it was quickly discovered that the direction of the blow was a factor of prime importance. Delivered vertically it produced fog. If hori-

zontally, it did not. A slanting blow gave fog of less density than a vertical one of the same force. Clearly the slight vertical displacement caused by the blow was the cause of the fog, but the manner of its working was not at once apparent.

A little consideration, however, led us to recognize that one portion of the apparatus was capable of a slight motion, or rather vibration, independently of the rest. Moreover, this motion was exclusively vertical in direction and was calculated to produce small but rapid changes in the volume of carbon dioxide. The part referred to is the mercury column in the glass pressure tube.

It is obvious that this column is held in place vertically by the carbon dioxide above and the steel walls of the pressure jacket below. As both of these are elastic, the column is suspended as if between two springs of very high tension, and vertical vibration is thus theoretically possible. It seemed almost incredible, it must be confessed, that so minute a motion as might be expected on these grounds could have produced the fog, for the walls of the steel jacket were more than half an inch thick.

To test the point, a metallic strap was adjusted around the center of the jacket. The strap was provided with thumb screws by means of which pressure could be applied to the jacket. Tightening the screws would diminish slightly the volume of the jacket, and so, indirectly, the volume of the carbon dioxide.

The result was surprising. It is true we could not obtain any visible effect by tightening the screws, but with each release, even though slight, there appeared a fog of much greater density than had ever been secured by rapping. In fact the circumstances were such as to illustrate in most extraordinary fashion the sensitiveness of matter near its critical state to slight increase of volume. *This* fog was due beyond any question to a sudden increase in the volume of the carbon dioxide.

It was now possible to understand how a blow from without could produce the same effect. The immediate effect of a downward blow is to depress for an instant the entire apparatus with the exception of the mercury column. This column, by virtue of its suspension between springs, does not partake at once of the motion, but lags behind the apparatus as a whole. The situation, so

far as the carbon dioxide is concerned, is the same as if the apparatus remained stationary and the mercury column alone moved *upward*. Extra pressure is temporarily exerted in the tube, and the volume of the carbon dioxide is correspondingly diminished.

By the time the mercury begins to follow the apparatus downward, the latter has begun to rise. This condition produces just the opposite effect — a momentary decrease of pressure and increase of volume. The decrease of pressure is responsible for the gas bubbles in the liquid phase, and the fall of temperature which accompanies the increase of volume produces the condensation of droplets in the vapor. Both bubbles and droplets disappear again in the next instant when the column returns to its normal position.

Strictly speaking, the fog so produced is not a single flash, but a series of flashes of decreasing density, which cease when the motion of the column becomes sufficiently feeble. But the individual flashes follow each other so rapidly that they cannot be distinguished by the eye, and the series itself is only of momentary duration.

The explanation of the production of fog which has just been given assumes that the effect in both phases is due only to the fall of the mercury column and the consequent increase of volume in the carbon dioxide. It may be urged that the rise of the column also should produce condensation in the saturated vapor. It is quite true that condensation is effected in saturated vapor by decrease of volume, but under these circumstances it never assumes the form of droplets. Decrease in volume results in a rise of temperature in the vapor, which in so far tends to restrict condensation. This rise of temperature is most pronounced near the axis of the tube, where the compression is most nearly adiabatic, and is least felt at the walls which have the temperature of the bath. For this reason the condensation occurs on the walls, which are the coolest part of the system, and the liquid so formed adheres to the walls and flows downward upon them. We shall return again to this form of condensation in a later paper, in presenting some data as to the condition of matter above the critical temperature.

It is quite unnecessary to say that vapor bubbles could never be produced in the liquid phase by decrease of volume.

The next advance in our study will doubtless have been already anticipated. If a single blow causes a transient fog, a rapid succession of blows should make the phenomenon practically continuous.

To test this, a set of tuning forks of rather large size was brought into requisition, not without some misgivings it must be confessed, as to the adequacy of the force of their vibration. Each of the forks was tried in turn, while the carbon dioxide was held at a constant temperature. Each of them produced a transient fog at the moment when its stem was brought, not too carefully, into vertical contact with some part of the apparatus. This was clearly the result of the impact only, as in previous experiments. Only one of the forks gave rise *by its vibrations* to a fog of longer duration. The rest failed entirely to act as desired, even though they were caused to vibrate with much greater force than proved necessary in the case of the one referred to. The temperature of the bath at the time was still about 30°.

It may be noted in passing that the superiority of the single fork would not have been nearly as pronounced, as we afterwards learned, and that all of the forks might in fact have produced fog, though of varying densities, if the temperatures had been a little nearer the critical temperature — at 31° for instance instead of 30°. This later discovery militates in no way against the obvious conclusion to be drawn from the experiment as described, namely, that none of the forks yielded vibrations of sufficient force in themselves to cause fog, and that one of them proved successful only because that one happened to be in resonance with the vibrating column.

If instead of applying the stems of the vibrating forks to the apparatus, the vibrating tines themselves were allowed to beat against it, all of the forks gave fog, but the effect in this case was transient again because the vibrations ceased almost immediately.

The extreme sensitiveness of the carbon dioxide to such minute changes of volume as were produced in these experiments by the vibrating mercury column is dependent upon a variety of factors, the discussion of which will be reserved for the present.

The essential features of the apparatus employed are illustrated in Fig. 1. *A* is the pressure jacket, the internal diameter of which is 3.8 cm., and the external diameter 6.7 cm. Its internal length,

measured from the gasket downward, is 19.4 cm. The valve *B* admits water from a hydraulic pump which is not shown, while the similar valve, *C*, leads to the pressure gauge. The pressure tube, *D*, has a capacity of 40 cc., and is mounted in a steel cap, *E*. The manner of the mounting has been described in a previous article.[1] The exposed end of the pressure tube has an internal diameter of 6 mm. and a thickness of wall of 2.5 mm. Both ends of the tube carry arbitrary graduations which were carefully calibrated with due regard to the curvature of the mercury meniscus. The lower end dips under a mercury seal in the jacket, while the upper end is surrounded by apbath which contains two liters of water, the temperature of which may be regulated by means of a very sensitive thermostat to one thousandth of a degree. The thermostat has already been described in detail.[2] For the present purpose it was found quite superfluous to read temperatures to more than two decimal places.

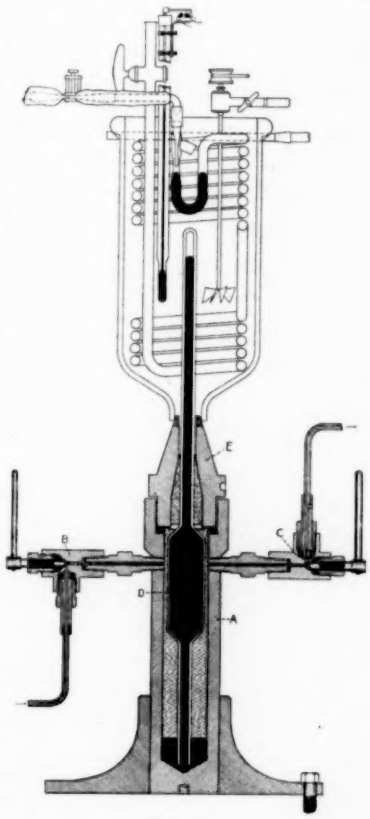

Fig. 1.

The pressure was read when necessary upon the eight-inch dial of a metallic pressure gauge. The gauge was carefully calibrated by comparison with an air manometer, due allowance being made for the deviation of air under pressure from Boyle's law.[3] But it should be said that the chief value of pressure readings in these experiments lay in the fact that they enabled us to detect the establishment of thermal equilibrium in the carbon dioxide more quickly

[1] Bradley and Browne, Journal of Physical Chemistry, **8**, 37, 1904.
[2] Bradley and Browne, Journal of Physical Chemistry, **6**, 118, 1902.
[3] Amagat, Comptes Rendus, **99**, 1153, 1884.

and precisely than in any other way (except indeed by the fog itself, as will appear later). The dial was graduated to thirds of an atmosphere (5 lbs.), and when the lag of the needle was corrected by gentle tapping upon the case, readings could be made with considerable accuracy to single pounds. The gauge showed no appreciable change of registration during the period of the experiments.

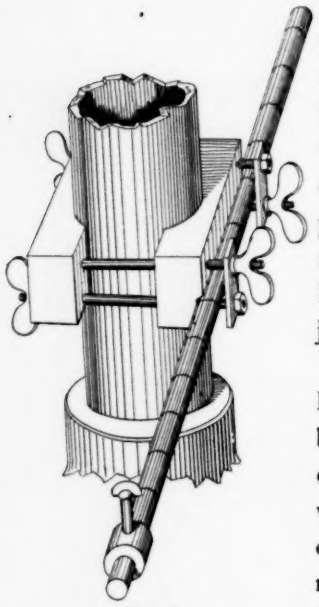

Fig. 2.

Much time was spent in efforts to determine the most practicable form of vibrator with which to induce the vibration of the mercury column. One device after another was tried and abandoned. The best one on the whole proved to be a simple cylindrical steel rod, about 1.1 cm. in diameter, attached horizontally to the center of the pressure jacket by means of an adjustable clamp.

From experiment to experiment the length of the vibrating portion could be changed at the clamp so as to secure coarser changes of pitch, while the finer variations required during the progress of an experiment were provided for by means of sliding weights. These could be fixed by means of suitable setscrews at any point upon the rod. The vibrations were produced by drawing the bow of a bass violin across a suitable point near the end of the rod. This method of inducing vibrations is superior in one respect at least to the electrical one. It permits of instantaneous changes of amplitude of a very wide range, which is an important factor. Direct comparison with a monochord gave the pitch of the rod. It is needless to say that the bow had to be drawn vertically to produce the fog.

Fig. 2 illustrates the vibrator, and the way in which it was clamped to the pressure jacket.

The carbon dioxide employed in the experiments was generated by the action of chemically pure boiled sulphuric acid upon sodium carbonate, later upon sodium bicarbonate. As some discussion of

pure carbon dioxide and the precautions necessary in its production will be given in another place, it may be sufficient at this point to add that the amount of impurity (unabsorbed by caustic potash solution) found in the various samples employed varied from one part in 5,000 to one in 40,000, and that the purity tests were made upon gas which had passed through the pressure tube during the act of filling it. The sample of least purity showed a difference of less than one fifth of an atmosphere between the pressures of initial and final liquefaction, while with the best sample the difference fell below the error of reading upon the gauge. It seems clear, therefore, that the phenomena which are associated with the production of fog in the carbon dioxide cannot be ascribed to the effect of impurities in the gas, particularly as there was no discernible difference in the conduct of the different samples in these respects.

The observations so far gathered upon the effects of vibration fall naturally into two classes. One of these contains the results of certain attempts at quantitative study, while the other includes a number of qualitative, and to some extent disconnected, phenomena, which seem to us nevertheless from a theoretical standpoint of rather more importance than the former. Only the former are given in this paper.

Such quantitative data as we have were secured during an attempt to determine the relation between the length of the mercury column and the most effective pitch of the vibrator. It seemed of considerable importance to determine whether the theory of resonance already given in explanation of the genesis of the fog might not be confirmed in this way. If the theory is correct, a longer column, under otherwise equal conditions, should correspond to a lower pitch.

The only practical way of changing the length of the column without interfering with other conditions was to alter the quantity of mercury which served as a seal in the lower part of the jacket. In the tables below one of the lengths of column corresponds to the smallest total quantity of mercury which could safely be used when the carbon dioxide was all liquid and therefore at its minimum volume; another, to the greatest quantity which could be used without danger of overflowing into the valves when the carbon

dioxide stood at atmospheric pressure, that is, at its greatest volume; and the third was intermediate between these two.

For the object in view it might have sufficed to make but three observations only, one for each length of the mercury column. It had been observed, however, that the vibratory period depends also upon the temperature of the carbon dioxide. Accordingly for each length of the column a number of tests were made at different temperatures. Still another factor demanded recognition, namely, the position of the meniscus in the system, or in other words, the relation between the volumes of liquid and vapor. The influence of this factor was too great to be neglected, particularly at the lower temperatures, and consequently for each length of column and for each temperature the dependence of pitch upon this relation was studied.

Production of fog either in the vapor or in the liquid is practically limited to the saturated condition, so that the tables refer to the two-phase system only.

It will be noted that the thermal range of the observations is only 2.2 degrees. The upper limit for instance is 31.2°. This does not mean that fog ceased at that temperature, but that it became very difficult indeed to determine accurately the position of the meniscus at temperatures higher than that. The lower limit is 29°. This in turn was not the point at which fog ceased to appear. The lower the temperature the greater the amplitude of vibration required to produce fog. Below 29° the necessary vibrations were of such force that the thermostat was often seriously disturbed, in spite of the fact that it was specially provided with a soft-rubber buffer for the sake of avoiding such an effect. It seems unlikely, however, that fog could have been obtained at a temperature much more than half a degree lower, without the substitution of direct blows for the bowing of the vibrator.

In the tables, the length of the mercury column represents the vertical distance between the upper meniscus, the position of which was read directly, and the lower meniscus within the jacket, the height of which was determined by calculation. Both levels are referred to a temperature of 30° and to the minimum (all liquid) volume of the carbon dioxide.

TABLE I.

Mercury column = 37.54 *cm.*

I. Temp.	II. Pitch.	III. Vapor Length.	IV. Total Length.	V. Vapor Volume cmm.	VI. Total Volume cmm.
30.2°	137.0	3.0	10.5	4.5	123
	132.7	5.0	10.75	19.0	128
	127.8	5.75	11.0	28.0	133
	124.3	6.75	11.25	42.0	138
	121.9	7.25	11.5	51.0	143
	115.0	9.0	12.25	83.0	159
31.0	110.4	4.0	11.0	9.0	133
	109.3	6.0	11.5	31.0	143
	106.8	7.0	11.75	46.0	149
	104.2	9.0	12.25	82.5	159
	103.4	10.0	12.5	102.0	164
	102.0	11.0	13.0	123.0	175
31.2	97.9	4.0	11.0	9.0	133
	96.8	6.0	11.5	31.0	143
	95.9	8.5	12.0	74.0	154

TABLE II.

Mercury column = 35.66 *cm.*

I. Temp.	II. Pitch.	III. Vapor Length.	IV. Total Length.	V. Vapor Volume cmm.	VI. Total Volume cmm.
30.0°	138.2	3.75	10.5	7.9	123
	132.7	6.25	11.0	34.5	133
30.2	134.7	3.0	10.5	4.5	123
	132.7	5.0	10.75	19.0	128
	126.6	6.75	11.25	42.0	138
	115.5	9.0	12.25	82.5	159
	106.8	11.0	13.0	123.0	175
30.5	132.7	2.5	10.5	2.5	123
	129.4	4.5	10.75	13.5	128
	122.4	6.75	11.25	42.0	138
	104.6	11.0	12.75	123.0	170
	102.7	12.0	13.25	144.0	180
31.2	110.4	2.75	11.0	3.5	133
	108.3	5.5	11.25	24.5	138
	102.7	9.25	12.0	87.5	154

TABLE III.

Mercury column = 33.78 *cm.*

I. Temp.	II. Pitch.	III. Vapor Length.	IV. Total Length.	V. Vapor Volume c.mm.	VI. Total Volume c.mm.
29.0°	145.8	2.0	10.0	1.25	112
	142.0	4.5	10.25	13.5	117
	136.8	6.0	10.75	31.0	128
	133.0	7.0	11.0	46.0	133
	129.1	7.5	11.25	55.0	138
	127.3	8.25	11.5	69.0	143
30.0	143.5	1.75	10.5	1.9	123
	137.4	5.25	10.75	21.75	128
	126.6	7.75	11.5	60.0	143
	120.0	9.0	12.0	83.0	154
	105.7	11.25	13.0	128.0	175
30.5	135.1	4.5	10.75	13.5	128
	123.5	6.75	11.25	42.0	138
	116.0	8.5	12.0	74.0	154
	111.7	9.0	12.0	83.0	154
	111.0	9.5	12.25	93.0	159
	108.3	10.5	12.75	113.0	170
	106.8	11.0	12.75	123.0	170
31.0	116.0	2.75	11.0	3.5	133
	112.1	6.0	11.5	31.0	143
	110.4	8.0	12.0	64.0	154
	106.8	10.0	12.5	102.0	164

Column I. contains the temperatures; Column II., the pitch required to produce fog of greatest density with least vibratory amplitude; Column III., the observed length of the vapor phase in divisions of an arbitrary scale; Column IV., the total length of carbon dioxide of both phases (chiefly for comparison)[1]; Columns V, and VI., the calculated gas and total volumes, respectively, in cubic millimeters.

In the diagrams which follow, abscissas represent the volume of the vapor, and the ordinates the number of vibrations per second. Each diagram corresponds to the table of the same number.

[1] For reasons which need not be discussed as yet, these phenomena cannot be studied to advantage in narrow tubes. The use of comparatively wide tubes however made it difficult to recognize small changes of volume except in the more or less conical tip. This accounts for certain apparent anomalies in the fourth and sixth columns.

Diagram I. (Table I.).

Diagram II. (Table II.).

Diagram III. (Table III.).

An inspection of these diagrams reveals the following facts:

1. The longest mercury column corresponds to the lowest pitch. The thesis, to test which the readings were taken, is proved. The curve of any given temperature is lowest in Diagram I., and highest in Diagram III.

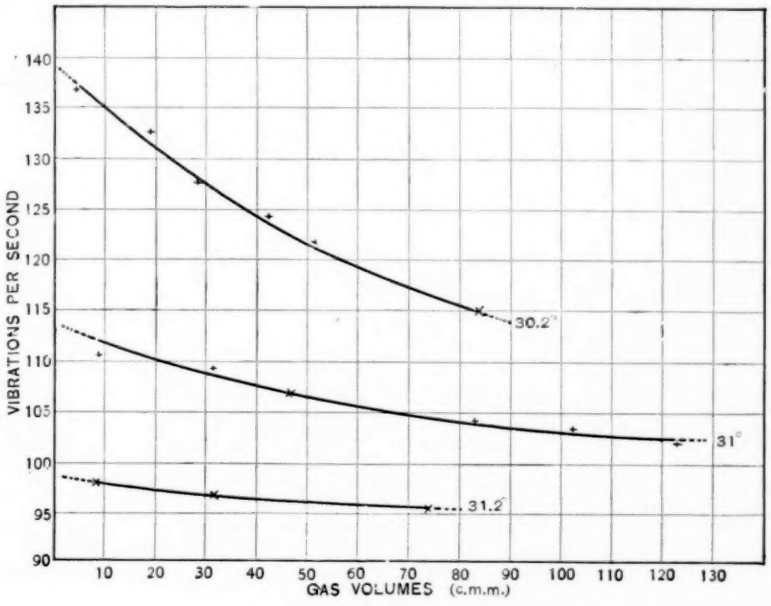

Fig. 3.

It is a curious circumstance, however, that the difference in the height of corresponding curves is greatest for temperatures nearest the critical, and practically disappears for the lowest temperatures in the tables. Thus, the curve of 31.2° in Diagram I. is much lower than that of the same temperature in Diagram II. The curve of 31.0° in Diagram I. is considerably lower, though less so, than that in Diagram III. That of 30.5° in Diagram III. approaches still more nearly the level of the corresponding curve in Diagram II., while there is hardly any difference at all in the height of the curves of 30.2° in Diagrams I. and II. We are quite unable to account for this rather striking peculiarity.

2. For a given length of mercury column, and for a given vapor volume, higher temperature corresponds to a lower pitch. This fact is very noticeable indeed.

If one thinks of change of temperature as affecting only the pressure of the system, this conclusion must seem astonishing. On this basis, rise of temperature, causing as it does an increase in the pressure of the carbon dioxide, should, in the language of our theory, increase the tension of the springs which control the vibrating mercury column. But increased tension means increased promptness of restitution, or in other words, *higher* frequency of vibration.

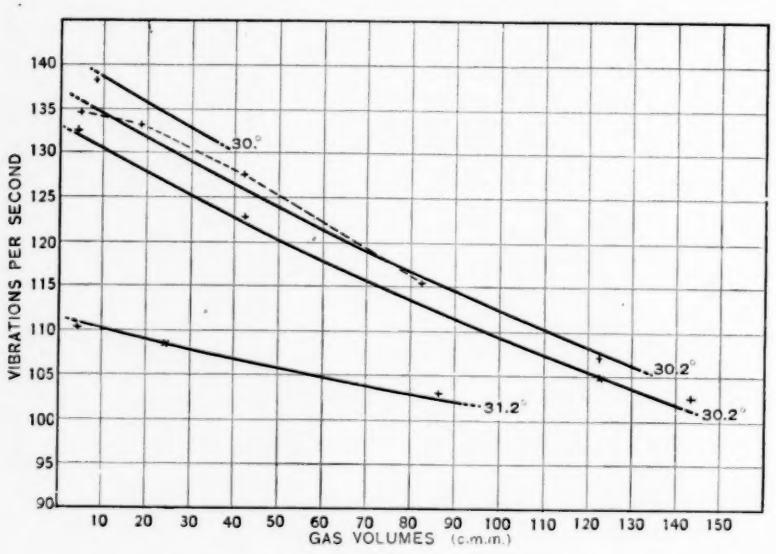

Fig. 4.

Rise of temperature has another result, however, whose effect may perhaps account for the observed reversal of this order. It is well known that the latent heat of a substance rapidly approaches zero in the immediate neighborhood of the critical temperature. Decrease in latent heat means a decrease in the amount of energy required to convert a given mass of saturated vapor into saturated liquid, or *vice versa*. Now copious liquefaction in the vapor phase must interfere with the power of restitution of this "spring," and make it relatively less prompt in reversing the motion of the mercury column. To repeat, rise of temperature tends on the one

hand to weaken the effect of the spring by decreasing the latent heat of the vapor, and on the other, to strengthen it by increasing the pressure. If the former effect is relatively greater, as it may be in such close proximity to the critical temperature, the relation between higher temperature and lower pitch would be explained. This matter deserves further study.

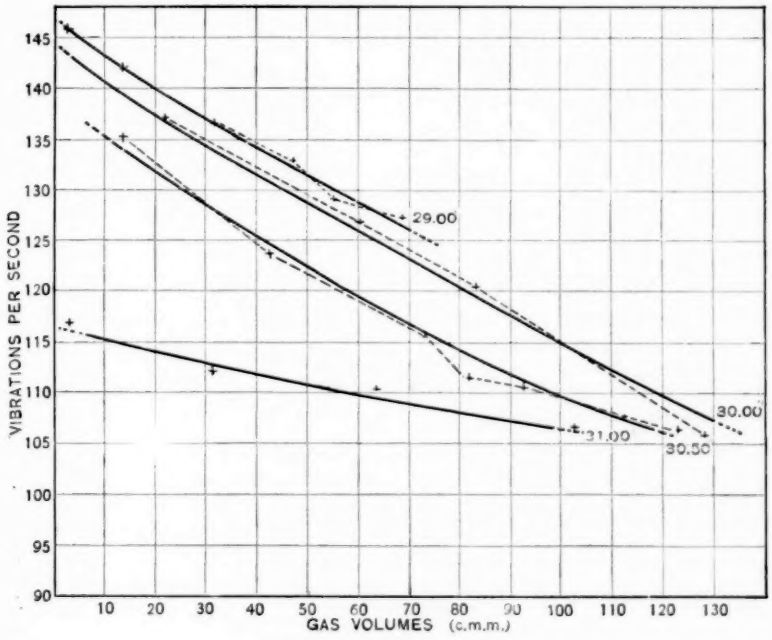

Fig. 5.

There is one other factor which helps, in a small way indeed, to an understanding of the connection of higher temperature and lower pitch. With a given vapor volume, higher temperature means a smaller total volume of carbon dioxide, and consequently a longer mercury column. As we have seen, lengthening the column lowers the pitch. To be sure, the increased length thus gained is very slight as compared with those considered in (1), and cannot play more than a relatively insignificant part in the problem now under discussion.

3. For a given length of mercury column, and for equal increments of temperature, the curves of pitch become more and more

widely separated as the critical temperature is approached. This is probably to be explained by the increasing rapidity with which the latent heat diminishes in this region as the temperature rises. The line of reasoning would be similar to that of (2).

4. (*a*) All else being constant, the pitch depends on the relation between the volume of the vapor and that of the liquid, or, to state it more simply, on the height of the meniscus in the carbon dioxide. The higher the meniscus the higher the pitch.

This result was to have been expected. Of course it is the more compressible vapor phase which constitutes the more effective portion of the upper "spring." The smaller the proportion of the vapor phase the greater the relative displacement produced in it by vibrations of given amplitude, and the greater the force of restitution, that is, the more rapid the vibration.

(*b*) This influence is greatest at lower temperatures. At higher temperatures the two phases resemble each other more and more closely in compressibility as in every other way. Thus, their relative volumes are of less moment, and the curves of pitch are flatter.

WESLEYAN UNIVERSITY,
MIDDLETOWN, CONN.,
May 21, 1904.

THE COMPARISON OF SMALL INDUCTANCES AT HIGH FREQUENCIES.

By A. H. Taylor.

CAPACITIES of the order of 10^{-11} farads have been measured with fair accuracy [1] but the measurement of correspondingly small inductances is more difficult.

By using an optical telephone with a bridge method, Wein [2] succeeded in measuring inductances of the order of 10^{-6} henrys to within less than 1 per cent. of their calculated values, using a frequency of 256. While this method is one of great percision, it is not applicable to the comparison of inductances at very high frequencies.

Seiler [3] measured inductances at high frequencies, his method in volving a measurement of a capacity, and of the period by a modification of the pendulum method of Helmholtz. The smallest inductance he measured was comparatively large, 316×10^{-6} henrys.

M. E. Maltby [4] measured both periods and inductances at high frequencies, in terms of capacity and electrolytic resistance. At a periodicity of 2.56×10^{-7} her results agree within 1.2 per cent. of the theoretical value of the period, but at higher frequencies there is a wide discrepancy.

Small capacities have been compared with small inductances at high frequencies by the use of the Nernst differential exciter. Battelli and Magri [5] using this method measured as small an inductance as 3.6×10^{-6} henrys. Judging from what details of the measurement they give, their limit of error was about 1 per cent.

[1] Fleming and Clinton, Phil. Mag., May, 1903.
[2] Ann. der Phys., p. 928, 1894.
[3] Ann. der Phys., p. 923, 1897.
[4] Ann. der Phys., p. 553, 1897.
[5] Phil. Mag., January, 1903.

Martienssen[1] using a modification of the method of "Phasenverschiebung" measured 2.5×10^{-6} henrys with great accuracy at a frequency of 500. His method could probably be extended to moderately high frequencies.

There are two criticisms to be made upon any form of bridge balance of inductance at high frequency. First, the difficulty of avoiding the reactions of neighboring parts of circuits. This objection can be partially removed by widely separating the inductances to be compared by the use of bifilared leads. In the case of very small inductance, the leads are not negligible, while in any case they act like a capacity in parallel with the inductance. Second, the high frequency currents used to operate the bridge must unavoidably have a pronounced group frequency, and the balance attained may not be a true high frequency balance.

It was in order to avoid these two difficulties that I had recourse to a resonance method which affords at the same time a determination of the period with very fair accuracy.

Let C_1 be a capacity in series with a spark-gap and the inductance L_1, while from two points a few centimeters apart on the circuit is run an auxiliary circuit consisting of the capacity C_2 in series with inductances L_e and L, and having an iron-constantin junction at T. The inductance L may be varied by moving the slider S, until the auxiliary circuit is in resonance with the main circuit, which will be indicated by the maximum deflection of the galvanometer connected with the iron-constantin junction at T.

If the point E be kept earthed the auxiliary circuit cannot appreciably affect the period of the main circuit. When in resonance, the auxiliary circuit, of low resistance throughout, needs only a very small potential difference to actuate it. Hence the main circuit may under favorable conditions be tapped by the auxiliary circuit at points distant only two centimeters on a No. 14 copper wire.

L_e is a circle of copper wire of diameter .146 cm. The diameter of the circle is 31.86 cm. The value of L_e according to the formula :[2]

$$L_e = 2l' \left(\log. \frac{l'}{R_1} - 1.5 \right)$$

is 1,154 cm., where l = circumference of circle R = radius of wire.

[1] Ann. der Phys., p. 95, 1899.

[2] Drude, Physik des Aethers, p. 361.

The mercury cups connected to this inductance occupy 1 cm. of the circumference. Applying an approximate correction,

$$L_c = 1{,}143.$$

In order to test the accuracy of the method, the auxiliary circuit was brought into resonance with L_c in, and then with L_c cut out, the difference in self-induction being compensated by moving the desirl S, whose position was read on a meter scale.

TABLE I.

L_c in.	L_c out.	ΔL.
40.0	95.0	55.0
40.0	95.0	55.0
40.1	94.9	54.8
39.7	94.9	55.2
		Average 55.0

The main circuit was excited by an induction coil as a step-up transformer, the spark-gap being in oil.

The parallel wires are of diameter .146, and are 10.08 cm. distant (d) from each other. The inductance added by shifting the slider a distance $\Delta L = 55$ cm. may be computed from the formula :[1]

$$L = 4\Delta L\left(\log\frac{d}{R} + \frac{1}{4}\right),$$

since the slider itself is a thick brass bar whose inductance may be neglected. The change in L is hence 1,139 cm., which compared with the computed value of L_c (1,143) shows an error of 0.35 per cent.

This is a fair sample of the accuracy with which two inductances of the order of a micro-henry may be compared by this method. The total value of L need not be known ; in fact it would be difficult to compute L for a practical case. But the change in L can be computed easily, and according to these observations may be relied upon to within one third of one per cent.

The capacity C_2 should be variable, and kept as large as possible and still allow the attainment of resonance, since greater accuracy

[1] Drude, loc. cit.

will be possible when the change in L is a large part of the whole inductance of the auxiliary circuit.

The mutual action of parts of the circuits should be prevented as much as possible. For the greatest precision, an unknown self-induction (in the place of L_c) should be measured in three pairs of positions 90° apart. The average will nearly eliminate disturbing effects due to mutual induction with neighboring parts of the circuit. Since the leads to L_c need not be known, it can be placed at some distance from the rest of the circuit.

If a variable self-induction is to be calibrated, the slider S can be moved so that L is as small as possible. Then the maximum value of the self-induction must be inserted at L_c and the capacity C_2 varied until resonance is attained. Then L_c can be decreased in steps, the circuit being brought back to resonance on increasing L by moving S. The increase in L can then be calculated, and is equal to the decrease in L_c. If the lowest value at L_c is greater than the range of change in L, this lowest value can be obtained by comparison with other known small inductances connected in series.

The method is not applicable to the comparison of inductances whose resistances differ so widely as to seriously affect the period of the auxiliary circuit, unless a compensating inductionless resistance be inserted in the auxiliary circuit.

The same set-up may be used with advantage to determine the period of the auxiliary, and hence of the main circuit.

Since there is no spark-gap in the auxiliary circuit, its resistance is constant and may be kept as low as a few tenths of an ohm. Hence the period is:

$$T = 2\pi\sqrt{LC_2}.$$

Now let the capacity C_2 take a new value, C_2', and let the change in L (as computed from the distance the slider S is moved) be dL.

Let

$$C_2' = C_2 - dC.$$

Then

$$\frac{T^2}{4\pi^2} = LC_2 = (L + dL)(C_2 - dC), \tag{1}$$

or

$$\frac{L}{C_2} = \frac{dL}{dC} - \frac{dL}{C_2}, \tag{2}$$

Dividing (2) by (1):

$$\frac{1}{C_2^2} = \left[\frac{dL}{dC} - \frac{dL}{C_2}\right]\frac{4\pi^2}{T^2}.$$

Hence

$$T = 2\pi\sqrt{\frac{C_2 C_2'}{C_2 - C_2'}}\sqrt{dL}. \qquad (3)$$

The capacities may be determined with great accuracy; hence that which determines the limit of error is the factor $\sqrt{dL}$. In a specific case,

C_2 was 0.00658×10^{-6} farads;

C_2' was 0.00474×10^{-6}.

Table II. shows the setting of the slider to determine dL.

TABLE II.

R_1	R_2	$R_1 - R_2$
91.8 cm.	37.8 cm.	54.0 cm.
91.4	37.7	53.7
91.6	37.5	54.1
91.5	37.5	54.0
91.5	37.6	53.9
		Average 53.94 cm.

R_1 is the setting for resonance with C_2 and R_2 the setting for C_2'. The value of dL corresponding to 53.94 cm. of the parallel wires is 0.9566×10^{-6} henrys, while the maximum variation in $R_1 - R_2$, hence in dL, is less than 0.8 per cent.

We are therefore sure of $\sqrt{dL}$ within 0.4 per cent., and the period as computed from (3) is 0.7997×10^{-6}. Allowing for a small possible error in the determination of the capacities, we may rely upon this value of T to within one half of one per cent.

An approximate calculation showed that the resistance of the auxiliary circuit would have to amount to 2 ohms in order to affect the period one tenth of one per cent. Since the actual resistance was only a few tenths of an ohm, there is no appreciable error involved in neglecting the resistance in calculating the period from (3).

The same values for C_1 and C_2 may be used to measure periods

over a considerable range, the periods being in such case proportional to $\surd dL$.

Several periods were measured, Table III giving the settings of the slider for the shortest period measured, C_2' was 1.004×10^{-10} farads, C_2 was 1.670×10^{-10}.

TABLE III.

R_1	R_2	$R_1 - R_2$
86.5 cm.	67.0 cm.	19.5 cm.
88.0	66.5	21.5
87.0	68.0	19.0
		Average 20.0 cm.

The parallel wires in this case were of diameter 0.146 as before, but their distance d was 5.85 cm. making:

$$dL = 0.3706 \times 10^{-6}$$

and

$$T = 6.07 \times 10^{-8}.$$

The maximum variation of $R_2 - R_2$ amounts here to 7.5 per cent., and the value of the period can be relied upon to only 3.8 per cent. Part of the difficulty in obtaining consistent values of $R_1 - R_2$, hence dL, was due to the fact that the iron-constantin couple was

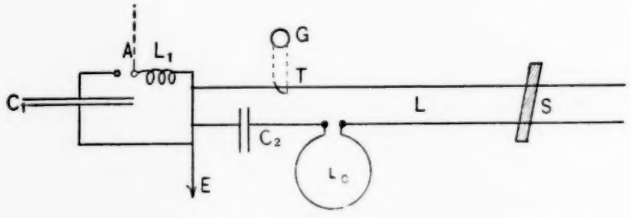

Fig. 1.

connected to a high resistance D'Arsonval galvanometer, not suitable for low resistance work and the deflections were small. I think it safe to say that by using a sensitive low resistance galvanometer the method could be applied to the measurement of periods of the order of 2×10^{-8} with a probable error of about 4 per cent.

This method is somewhat similar to one suggested by Drude,[1]

[1] Ann. der Physik, p. 611, 1902.

the difference being that while he computes both C_2 and L, this method involves the measurement of C_2 and C_2', and the computation of dL, dispensing with the consideration of parts of the circuit awkward to compute.

In case the main circuit with the spark-gap is a radiating circuit, *i. e.*, if a tuned aërial be connected with it, a second aërial several meters distant may be tuned to it, and the auxiliary circuit tapped off from this receiving aërial, hence avoiding any possible direct influence of the auxiliary circuit upon the period of the main circuit.

A series of observations similar to those in Table II. for such a case showed a period of 0.710×10^{-6}, and a possible error of 0.4 per cent.

The double resonance makes it possible to determine dL with somewhat greater accuracy, so that for periods of this order it is better than the simpler method.

TABLE IV.

R_1	R_2	R_2-R_1
Circle.		
12.0	17.8	5.8
11.5	17.5	6.0
11.2	17.2	6.0
11.5	17.5	6.0
Square.		Average 5.95
12.0	16.7	4.7
12.1	17.1	5.0
12.2	17.0	4.8
11.8	16.6	4.8
		Average 4.825

In order to see what could be done in comparing still smaller inductances, the inductance L of the main circuit was made of parallel wires distant 5.85 cm. and of diameter 0.146, and provided with a slider.

A tuned aërial was connected at A, and a tuned receiving aërial with the auxiliary circuit branching off from it was placed 2.5 meters distant from the transmitting aërial. The auxiliary circuit was brought into resonance and left so permanently, the galvanometer

showing a maximum deflection. The small inductance to be measured was now inserted in the main circuit in series with the now variable L_1, and throwing the main circuit out of resonance with both transmitting and receiving aërials, also with the auxiliary circuit. L_1 was then varied by moving the slider until resonance was attained again. Table IV. gives the results for:

1. A circle of wire of diameter 0.146, diameter of circle 4.82 cm.
2. A square of the same wire 2.8 cm. on a side.

The computed inductance for the circle is 116×10^{-9}, while by comparison with dL, it is 110×10^{-9} showing a discrepancy of 5.3 per cent.

The inductance of the square considered as a combination of two sets of parallel conductors, and computed from the formula:

$$8S\left(\log \frac{S}{R} + \frac{1}{4}\right) = L,^{1}$$

where $S =$ side of square, was 87.29×10^{-9}.

As compared with dL, the inductance of the square was 89.4×10^{-9}, the discrepancy being 2.3 per cent.

The variation in $R_2 - R_1$ indicates, however, that these results cannot be relied upon closer than to within 6 per cent.

PHYSICAL LABORATORY,
UNIVERSITY OF WISCONSIN, April 27, 1904.

[1] Drude, loc. cit.

SOME PHYSICAL PROPERTIES OF CURRENT BEARING MATTER. I. TENSILE STRENGTH. II. MELTING POINT.

By Paul R. Heyl.

A DESCRIPTIVE résumé of the work that has been done in determining the physical properties of current bearing matter will be found in the Journal of the Franklin Institute for March 1904. The object of the present article is to present the results of some additional investigations in this matter. It may be stated at once that the results about to be presented are negative. Any change in the tensile strength of iron for a current density of 2,000 amperes per square centimeter cannot exceed one half of one per cent., and for copper, with a current density of 1,000 amperes per square centimeter, the alteration cannot exceed one fifth of one per cent. Any change in the melting point of tin for a current density of about 2,500 amperes per square centimeter can hardly exceed 2°. There is some reason to believe that a more powerful method would definitely show a small rise in the melting point.

Tensile Strength.

The substances tested were iron and copper in the form of wire. To eliminate the heating effect the wire under test was kept surrounded by a stream of cold water. Fig. 1 shows the arrangement of the apparatus. *BC* is the fine wire to be broken, stretched vertically between stronger wires in the axis of a glass tube of about two centimeters diameter. The lower end of this tube is closed by a cork *D* provided with a large hole through which one wire passes loosely on its way to a projecting support below. The upper end *A* of the tube is open, and the other wire passes out and is continued by means of a fish line over two pulleys to a pan with weights. A stream of water from the faucet is introduced at *A*, fills the tube to overflowing and escapes freely through the hole

at *D*. The waste water falls into a sink over which the apparatus is set up. The temperature of the water is taken by a thermometer which hangs in the tube. When the wire to be broken carried a current this was provided by a storage cell in connection with a suitable rheostat and an ammeter reading 0.05 ampere, the terminals being loosely hooked to the wires at *A* and *D*.

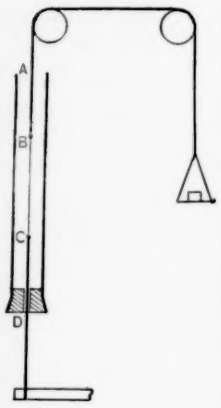

Fig. 1.

To the weights in the pan at the time of breaking is to be added a correction consisting of the weight of the pan itself minus the static friction of the cord and pulleys. The weight of the pan was nearly 100 grams, and the friction was about half a gram. As the weight in the pan was always greater than 1,000 grams, and was never increased by less than 5-gram steps, the friction was neglected and the correction considered to be an even 100 grams.

To insure that the test wire should break between the points *B*, *C*, at which it was fastened (by twisting) its middle part was slightly reduced in diameter by rubbing it with emery paper, any slight ellipticity of cross section thus introduced being allowed for by measuring the diameter in two perpendicular directions. In Tables II., III. and IV., the diameter given was measured after breaking, at the broken ends. In Table I. the diameter is that before breaking. This was obtained by measuring the diameter in three places, the thinnest part and a little on each side of it, and recording the diameter at the point nearest which the break afterward occurred, which in nearly every case was the thinnest point. This proved a somewhat unsatisfactory method, but as the result of Table I. is merely a small correction to the result of Table II., it is amply accurate for the purpose. Of course, the resulting tensile strength in Table I. would be slightly different from the corresponding value in Table II., but as comparisons are made only within each table and not between the tables this is of no moment.

Tables II. and IV. contain the results of the experiments on the tensile strength of the wire with and without a current. These experiments extended over several days, and in consequence the

temperature of the tap water varied somewhat. It was therefore thought advisable to determine the effect of the variation of temperature upon the tensile strength. These results are found in Tables I. and III. As the extreme range of temperature in Tables II. and IV. is but 6°, an approximate value of the temperature coefficient is all that is necessary. To determine this the apparatus shown in Fig. 1 was slightly modified. The cork with the large hole *D* was replaced by another in which the wire fitted tightly; the water in the tube remained stationary, and was heated, when desired, by conducting into it a current of steam. It was found that the temperature coefficient for iron was negligible, but that for copper this correction could not be disregarded.

A word of explanation may be necessary concerning the mode of tabulating the results. The tensile strength of a wire is by no means uniform from point to point in the wire. To arrive at a correct idea of the average tensile strength one must break a great many short pieces and average the results. To determine the tensile strength as an end in itself it would be necessary to accumulate observations of this kind until the mean became practically constant; but this method of procedure may be shortened considerably if we desire to know only the ratio of the tensile strengths under two different conditions, such as heat and cold, current or no current. The experiments to be described were performed in this way: a spool of wire was cut into short pieces about 17 cm. long; the first, third, fifth, etc., were broken under the first set of conditions, and the second, fourth, sixth, etc., under the opposite conditions. The cumulative mean was calculated after each observation, as was also the ratio of the corresponding means. It will be seen from the tables that the ratio of the means approaches its limit more rapidly than does the mean value of the tensile strength. It is not claimed that the experiments described in Table I., have been pushed far enough to afford an accurate value of the temperature coefficient of cohesion in iron, but we may conclude from the last value in column 6 that the iron is not weakened more than about five per cent. for a rise in temperature of some 75°. We shall see that this may be neglected in the results of Table II.

By far the greatest error in the second table lies in the determi-

nation of the diameter. This was done by a micrometer caliper of 0.5 mm. pitch, graduated to hundredths of millimeters. The error in any diameter may be as much as one per cent., which would lead to an error in the area (and consequently in the tensile strength) of two per cent. The weights in the pan were added by 5-gram steps, making an error of less than one half of one per cent. The extreme range of temperature is 2.5°, by neglecting which we introduce an error of only one sixth of one per cent., according to the result of Table I. The current density is a little more than 2,000 amperes per square centimeter, and the last value in column 6 shows that any alteration of the tensile strength under a current of this intensity does not exceed one half of one per cent. Whether there is any effect less than this is doubtful; these figures can hardly be said to establish it, considering the error of a single observation.

From the last value in column 6 of Table III., we see that copper wire is weakened about fourteen per cent. for a rise of temperature of about 76°. It is worthy of notice that the values in column 6 are practically constant after the second observation while those in column 5 have not reached their limit in eight observations.

In Table IV., the greatest error, as in Table II., is in the diameter, but is somewhat less than in the former case for two reasons: because the quantity to be measured is greater, and because each diameter here recorded is the result of four measurements instead of two, as was the case with the iron wire. The error in the tensile strength arising from this measurement is probably about one per cent. The weights in the pans were added by 10-gram steps, introducing an error of about one third of one per cent., and the tensile strength is calculated to the uniform temperature of 20°, as the greatest error that would be introduced by neglecting this correction would be about one per cent. The current density in this case is about 1,000 amperes per square centimeter.

From the last value in column 6 of this table we see that any alteration in the tensile strength under a current of this intensity does not exceed one fifth of one per cent. and from the way in which the values in column 6 fluctuate above and below unity it is altogether likely that the current produces no effect at all.

Table I.

Effect of Temperature on the Tensile Strength of Iron Wire.

1. Diameter in mm. before breaking.
2. Temperature.
3. Weight in pan at breaking; grams.
4. Tensile strength in kg. per sq. mm.
5. Successive values of the mean tensile strength.
6. Ratio of the means (hot : cold).

1	2	3	4	5	6	5	4	3	2	1
0.200	23.1	1155	39.9	39.9	0.947	37.8	37.8	1135	100.2	0.204
188	24.5	1090	42.9	41.4	0.914	37.9	37.9	1115	100.2	202
201	24.1	1165	39.8	40.9	0.958	39.1	41.7	1265	100.3	204
202	24.7	1305	43.8	41.6	0.955	39.8	41.7	1185	100.3	198
203	25.1	1150	38.6	41.0	0.976	40.0	40.9	1120	100.3	195
201	25.2	1220	41.6	41.1	0.985	40.5	43.0	1120	100.3	190
206	24.9	1285	41.4	41.1	0.973	40.0	37.3	1335	100.4	221
200	24.5	1325	45.3	41.7	0.953	40.2	41.3	1250	100.2	204

Table II.

Effect of Current on the Tensile Strength of Iron Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in the pan : grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (current : no current).

Current Nothing.					Current 0.7 Ampere.					
1	2	3	4	5	6	5	4	3	2	1
0.210	21.9	1253	39.1	39.1	1.11	43.3	43.3	1260	21.8	0.200
.204	21.9	1208	40.0	39.6	1.03	40.6	37.9	1237	21.9	.212
.210	21.9	1160	36.4	38.5	1.02	39.2	36.4	1150	21.9	.209
.212	21.9	1120	34.6	37.5	1.02	38.3	35.4	1150	21.9	.212
.213	21.9	1270	38.4	37.7	1.02	38.3	38.5	1245	21.9	.211
.203	22.0	1220	40.8	38.2	1.02	39.0	42.4	1245	22.0	.201
.205	22.0	1240	40.6	38.6	1.02	39.2	40.5	1275	22.1	.208
.204	22.2	1285	42.4	39.0	1.008	39.3	40.3	1205	22.7	.203
.203	22.1	1200	40.2	39.2	1.007	39.4	40.1	1210	23.0	.204
.203	23.2	1235	41.3	39.4	1.012	39.9	43.7	1300	22.6	.202
.199	22.8	1225	42.6	39.7	1.011	40.1	42.8	1300	23.3	.204
.203	24.3	1205	40.3	39.7	1.012	40.2	41.2	1245	23.4	.204
.200	23.5	1300	44.6	40.10	1.005	40.28	41.1	1230	23.3	.203
.203	23.3	1260	42.0	40.24	1.004	40.40	42.0	1245	23.7	.202
.200	23.8	1230	42.3	40.37	1.003	40.49	41.8	1240	24.0	.202
.201	24.1	1265	43.0	40.54	1.005	40.73	44.3	1335	23.8	.203

TABLE III.

Effect of Temperature on the Tensile Strength of Copper Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in pan: grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (hot: cold).

1	2	3	4	5	6	5	4	3	2	1
0.272	23.3	2500	44.7	44.7	0.72	32.0	32.0	2640	100.3	0.330
..365	22.7	2950	29.2	37.0	0.86	31.8	31.6	2600	100.1	.330
.307	22.5	2680	37.6	37.2	0.86	32.2	32.9	2580	100.2	.322
.308	23.7	2870	39.9	37.9	0.86	32.5	33.5	2530	100.1	.316
.324	24.1	3030	38.0	37.9	0.86	32.7	33.4	2500	100.1	.315
.322	24.7	3020	38.3	38.0	0.87	32.9	34.1	2700	100.1	.323
.310	24.5	2960	40.5	38.3	0.86	32.8	32.3	2630	100.1	.328
.315	23.4	2950	39.1	38.4	0.86	33.2	35.7	2540	100.1	.307

MELTING POINT.

The metal selected for this investigation was tin. The first method used was to immerse a thermometer directly in the molten metal. In order to get as great a current density as possible the arrangement shown in Fig. 2 was employed. The tin was melted in a hard glass test tube and a smaller tube of hard glass open at both ends was immersed in it, reaching nearly to the bottom of the melted metal. A thermometer was placed within the inner tube, its bulb being thus surrounded by a thin cylinder of molten metal which was in turn surrounded by a much larger quantity of the same substance. An iron-tipped wire coiled once around the thermometer bulb supplied the current to the inner shell of tin. The current passed down this shell, under the edge of the inner tube and out by another wire from the larger mass of melted tin outside.

Fig. 2.

The thermometer used was one of short range (200°–250°) graduated to fifths of a degree, and read with a lens to fiftieths. Its bulb was 0.55 cm. in diameter and about the same length. The inside diameter of the inner tube was 0.75 cm., thus leaving a thin cylinder of tin whose sectional area was about 0.21 sq. cm. The current used was 3 amperes, giving a current density of about 14 amperes per sq. cm.

TABLE IV.

Effect of Current on the Tensile Strength of Copper Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in pan : grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (current : no current).

Current Nothing.					Current 0.8 Ampere.					
1	2	3	4	5	6	5	4	3	2	1
0.331	24.4	3100	36.9	36.9	1.008	37.2	37.2	2930	22.8	0.321
.325	22.3	2900	36.1	36.5	0.999	36.5	35.7	3000	21.4	.332
.322	21.2	3000	38.0	37.0	0.978	36.2	35.7	3000	21.6	.332
.319	21.5	2940	37.9	37.2	0.969	36.1	35.7	2850	21.3	.324
.315	21.2	2950	39.0	37.6	0.967	36.3	37.4	2950	21.1	.322
.320	21.0	2940	37.7	37.6	0.975	36.6	38.1	2820	20.8	.312
.325	20.7	2870	35.8	37.4	0.989	36.9	38.6	2910	20.7	.315
.320	20.6	2860	36.8	37.3	0.993	37.0	37.7	2950	20.5	.321
.308	25.0	2700	37.2	37.3	0.990	36.9	36.1	2860	22.3	.322
.317	21.1	2840	37.1	37.3	0.995	37.1	38.3	2930	20.8	.317
.315	20.9	2850	37.8	37.3	0.990	36.9	35.8	2930	21.0	.328
.322	22.4	3020	38.2	37.4	0.994	37.2	39.7	3010	23.1	.315
.325	22.9	2850	35.4	37.2	1.003	37.3	39.5	2900	22.8	.310
.300	21.9	2800	40.9	37.5	1.002	37.6	40.3	2700	21.5	.297
.322	21.4	2880	36.5	37.4	1.007	37.7	39.3	3010	21.2	.317
.306	21.1	2740	38.5	37.5	1.003	37.6	36.5	2680	20.9	.311
.320	19.6	2860	36.8	37.5	1.003	37.5	36.7	2990	19.2	.328
.325	19.0	3100	38.7	37.52	1.001	37.55	37.7	2970	19.3	.322
.323	19.2	3080	38.9	37.59	0.999	37.54	37.2	2700	19.0	.310
.312	19.3	2830	38.3	37.63	0.998	37.56	37.9	2800	19.4	.312

It was found by some preliminary experiments that this current in the iron-tipped wire close to the thermometer stem produced no effect on the latter. To ascertain this the thermometer bulb was immersed in water and the current was led down and up close to its stem. In the actual test the liability to such an effect would be halved, as the return current was at a little distance from the stem with the wall of the glass tube between them.

The experiments on the melting point were conducted as follows: The tin was melted and raised to about 250°, and then allowed to cool. It usually fell a variable fraction of a degree below 230°, then rose to the constant melting point, finally falling slowly as the solid metal cooled. This operation was repeated alternately with and without a current in the tin with the following results:

Melting Point.	
Without Current.	With Current.
230.80	230.80
230.80	230.80
230.80	230.80

It is evident from this that the melting point of tin is not altered by as much as one fiftieth of a degree by a current density of 14 amperes per sq. cm. As the absolute melting point is unessential to this conclusion no correction was applied to the thermometer.

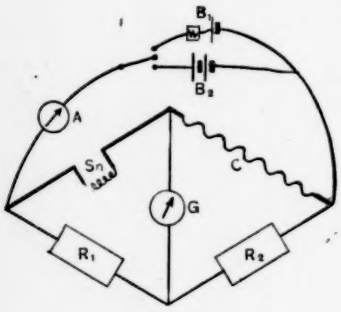

Fig. 3.

It was found impracticable to reach a very high current density by this method, and a second plan was devised. In outline, this was to use a strip of tinfoil of small cross section as one of the arms of a Wheatstones' bridge adapted to carry a current of two or three amperes, and determine the melting point of the tin by its resistance at the instant of melting. The details are shown in Fig. 3.

C, a standard one ohm coil.

A, an ammeter reading 0.05 ampere.

R_1, R_2, ordinary resistance boxes.

G, a D'Arsonval reflecting galvanometer.

B_1, a Leclanché cell with an additional resistance of 50 ohms.

B_2, two storage cells.

Sn, the tinfoil strip. To prepare this a sheet of tinfoil was cut as in Fig. 4, the narrow strip being 1 mm. wide and about 30 cm. long, while the wide parts were about 2.5 cm. wide. The wide parts were rolled up tightly to form handles for the strip, by means of which connection was made to heavy copper wires by screwconnectors. The narrow strip was wound on a small square of glass and tied on by a thread. The handles and connecting wires were vertical so that the strip on its glass plate could be hung in any desired liquid.

Fig. 4.

The resistance in the box R_2 was kept constantly 1000 ohms, and that in the box R_1 varied to make a balance. The resistance of the tinfoil strip was usually about one ohm when cold, so that the total resistance in the upper half of the bridge was about two ohms, while that of the lower half was a thousand times as great. Consequently, when a cell of no internal resistance, such as a storage cell, was applied to the bridge a heavy current would traverse the upper arms of the bridge and a feeble one the lower; and the current in the tinfoil strip would be very nearly equal to the current shown by the ammeter.

The standard one ohm coil was constructed of bare German silver wire 0.8 mm. diameter, used double and wound on a wooden block. It was kept immersed in kerosene, the temperature of which was noted by a thermometer. The coil was provided with short, heavy copper terminals dipping into mercury cups, which cups formed the terminal points of this arm of the bridge. The total resistance in this arm was measured against a standard correct to one part in a thousand, and was found to be 1.000 ohms at 18°. Its temperature coefficient was assumed to be 0.00044 for the few degrees that its temperature varied from 18°. It was found that the coil thus arranged would carry a current of one ampere for an hour with a rise of temperature of less than one degree.

The experiments were conducted as follows: a tinfoil strip having been put in place its resistance was measured at the room temperature in kerosene, by the feeblest current that would give a definite result. This was about 0.02 ampere, furnished by switching in the Leclanché cell B_1 with its additional resistance of 50 ohms. The temperature of the one ohm coil was noted. The strip was then hung in melted paraffin whose temperature was gradually raised with continual stirring until the tinfoil melted. As the temperature rose the resistance in R_1 was increased by one or two ohm steps to maintain the balance. The melting point of the tinfoil was indicated by a sudden throw of the galvanometer, the resistance in R_1 protecting the instrument from any excessive current. The temperature of the one ohm coil was again noted. The melted paraffin was removed, the handles scraped clean, bent toward each other and fastened by a clip, and the resistance of the connections measured.

From these data the resistance of the tinfoil strip was calculated at its melting point and at 20°. For the latter part of this calculation the temperature coefficient of tin was taken as 0.0037. We then obtain finally the ratio of the resistances of the strip at 20° and at the melting point, for a small current density.

Another strip was put in place, and the operations repeated, except that for the hot resistance the storage cells were used, sometimes in series, sometimes in parallel, according to the resistance of the strip, so as to furnish a current of about one ampere. The ratio of the resistances at the melting point and at 20° was calculated as before. As the current density was now small at 20° and great at the melting point any effect of the current on the melting point would show itself in the value of this ratio as compared with that obtained by using the weak current throughout. It was of course assumed that the resistance of tin is not a function of the current strength. While this has not been proved for the special case of tin it does not seem a dangerous assumption.[1]

The tinfoil strip was always about one millimeter wide and varied in thickness from 0.04 to 0.05 mm. Consequently the two current densities used were about 50 and 2,500 amperes per square centimeter in the thin parts of the strip. The varying thickness plays a curious part in the experiment. Its effect may be neglected for feeble currents, but for heavy currents any irregularity in thickness will reduce the apparent melting point, and the fewer the thin places the greater the apparent reduction. The thin parts, being more strongly heated by the current, will reach the melting point and break while the average temperature of the strip is below the melting point; and the fewer the thin places the lower will be this average temperature.

Experiments were made alternately with the weak and the strong current and the results are given in the following tables. A number of unrecorded experiments were made before the method was well in hand, and the experiments given are the last fifteen consecutive ones.

It will be noticed that the values in column 6 of Table V. depart less from their mean than do those of the same column in Table VI.

[1] See the résumé referred to at the beginning of this article.

TABLE V.

1. Temperature of the one ohm coil.
2. Temperature of tinfoil strip.
3. Resistance in box R_1.
4. Resistance of connections to tinfoil strip.
5. Corrected resistance of strip (for low temperatures, at 20°).
6. Ratio of resistances (hot : cold).

Current 0.02 Ampere.					Current 0.02 Ampere. Temperature, Melting.			
1	2	3	4	5	6	5	3	1
21.3	20.9	1136	0.008	1.125	1.537	1.729	1734	23.0
21.3	21.2	977	0.008	0.966	1.532	1.480	1486	22.0
20.0	18.9	1112	0.008	1.109	1.526	1.692	1698	20.1
17.6	16.7	1157	0.008	1.160	1.533	1.778	1786	18.4
20.1	19.0	843	0.008	0.840	1.549	1.301	1308	20.0
18.2	19.5	867	0.008	0.861	1.528	1.316	1324	19.4
20.3	20.0	891	0.008	0.884	1.520	1.344	1351	21.2
				Mean value	1.532			
				Average departure from mean	0.0065			

TABLE VI.

Current 0.02 Ampere.					Current 1 Ampere. Temperature, Melting.			
1	2	3	4	5	6	5	3	1
23.8	24.6	1160	0.008	1.138	1.520	1.730	1733	24.6
22.7	22.2	1437	0.008	1.423	1.526	2.171	2173	23.8
20.2	19.0	940	0.008	0.937	1.512	1.417	1424	20.4
19.0	18.7	1050	0.008	1.047	1.521	1.593	1601	19.8
19.8	19.0	831	0.008	0.826	1.553	1.283	1290	20.4
20.0	19.4	731	0.008	0.726	1.560	1.133	1140	20.3
21.9	22.9	947	0.009	0.930	1.565	1.456	1462	23.4
20.1	19.0	965	0.008	0.962	1.530	1.472	1480	19.9
				Mean value	1.536			
				Average departure from mean	0.018			

The cause is undoubtedly the higher current density in the latter case which causes the unavoidable irregularities of the strip to have a greater effect upon the result. The rise in temperature of the tinfoil increased its resistance in the ratio of 1 : 1.53, the excess of 0.53 being due to a rise of about 200°. The difference in the final means in the two tables is 4 in the third decimal place, and 4 parts in 530 for a rise of 200° would mean a difference of less than 2° in

the melting point. Are we justified therefore in concluding that the melting point of tin is raised by this amount under a great current density? Undoubtedly the results of Table VI. in themselves cannot be taken as proving this, so great is the average departure from the mean; but when we recollect that the effect of great current density upon an irregular strip is always to *decrease* the apparent melting point, and when we notice that several of the values of Table VI. are greater than any of the quite concordant values of Table V., it seems likely that there may be a small rise of the melting point under a great current density which would require closer measurements to prove its existence.

It is hoped to extend this investigation to some metals of much higher melting point in the near future.

CENTRAL HIGH SCHOOL,
PHILADELPHIA.

AN AUTOMATIC COMMUTATOR AND GALVANOMETER KEY FOR MEASURING PERIODICALLY RECURRING PHENOMENA.

By Arthur W. Gray.

IN an earlier paper[1] the writer described an apparatus which he had constructed for automatically placing a galvanometer in the circuit of a condenser (a Siemens ozone generator), which was being charged and discharged in rapid succession, just long enough to measure ballistically a *single* charge or discharge. Although this device answered fairly well the purpose for which it was intended, considerable room for improvement remained. In the first place it performed its function as a shunt of negligible resistance in parallel with the galvanometer, which was automatically removed at will when it was desired to obtain a deflection; so that during all but about 40 of the 12,000 to 25,000 passages of electricity that were effective in producing ozone, the resistance and self-induction in the circuit of the generator were negligible, while during the measurement of the quantity of electricity about 200,000 ohms and 27 millihenries were inserted. Whether this difference would alter the conditions within the generater could not at the time be known, but it seemed not at all improbable that it might exert a considerable influence, and that such was actually the case is clear from the results of the experiments to be described in a later paper.

Then again the mechanism was weak and more complicated than necessary, and was not suitable for use with potentials much over 15,000 volts.

To overcome these defects the writer designed the apparatus represented in orthographic projection by Fig. 1. By means of this the resistance and self-induction in the electrical circuit of the

[1] A. W. Gray, Ann. d. Phys., 13: p. 481, 1904.

generator could be kept the same whether the current passed

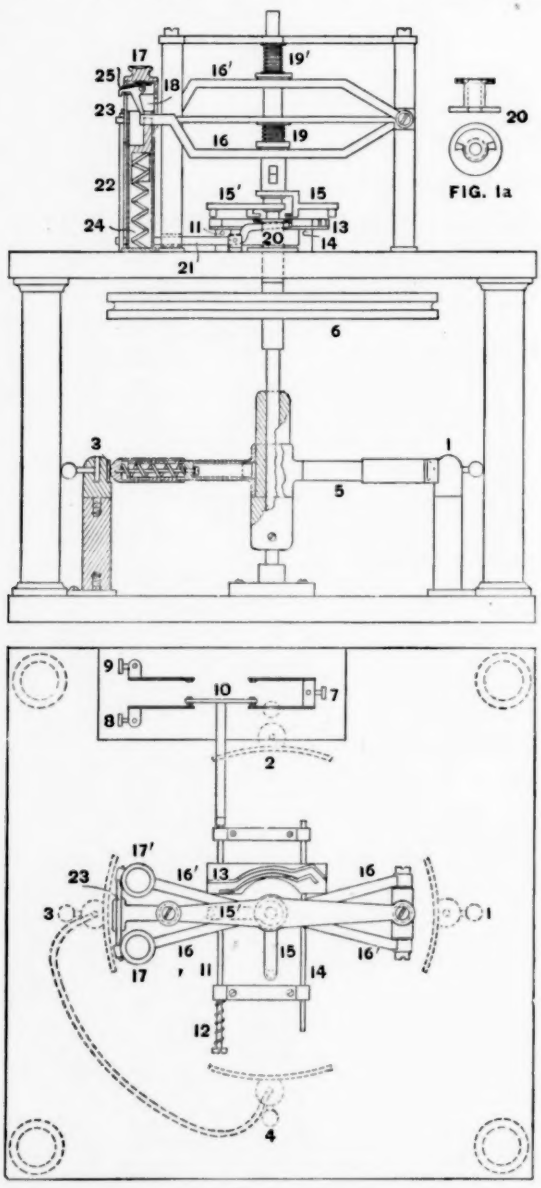

FIG. 1a

Fig. 1.

through the galvanometer or not; the insulation could be made as perfect as desired; rapidly reciprocating parts were replaced by

rotating ones, thus doing away with troublesome vibrations; the mechanism was simplified and made so much more durable that it would stand long-continued operation without the slightest attention beyond occasional oiling; the resetting after obtaining a galvanometer deflection was performed automatically, and the working was so positive that even many thousands of trials failed to disclose a single false move, even when the speed was made much greater than was necessary for the purpose.

It should be remarked here that, while the machine was designed for the purposes of the work in hand, its application is by no means limited to this. The essential ideas embodied in it can, in fact, be employed to advantage wherever it is desired to single out for measurement a phenomenon which recurs periodically, provided the intervals between recurrences are not too short.

The construction and working of the machine will be made apparent by a study of Fig. 1, which shows some parts in section for the sake of greater clearness.

The four well-insulated metallic terminals, 1, 2, 3, and 4 are uniformly distributed on the circumference of a circle; 1 is connected to the Leyden battery, 2 with the earth, 3 and 4 with each other and with the inner electrode of the generator. The metallic bar 5, insulated from the vertical axis about which it is turned by the pulley 6, has its ends provided with spring contacts which rub against the curved plates attached to the terminals, so that connection is made alternately between 1 and 3 and between 2 and 4, thus charging and discharging the generator in rapid succession.

Upon a shelf above the rotating commutator is located the mechanism that constitutes the galvanometer key. The wire from the generator leads to 7, while 8 leads through a resistance and self-induction equal to that of the galvanometer and 9 through the galvanometer itself to earth. Either 8 or 9 can be connected through spring platinum-tipped contacts with 7 by means of the metal bar 10. This is insulated and carried on the end of a rod 11 which slides in guides and by means of the spring 12 is held ordinarily in the position shown. The plate 13, which carries on its upper surface a grooved way shaped as indicated, is firmly attached to 11 and to the similar rod 14, which serves merely as a support and guide.

Two similar arms, 15 and 15′, are rigidly attached to sleeves surrounding the axle of the commutator 5, so that they turn with this but are free to be moved independently of each other a short distance along the axle. The two arms are fixed at right angles to each other as represented in the horizontal projection, although in the vertical projection 15 is represented as moved back 90° from its true position in order to show its shape. Ordinarily 15 and 15′ are held up in the position indicated by flanges at the upper ends of the attached sleeves resting on supporting collars carried by the levers 16 and 16′; so that the short rods projecting downwards at the extremities of the arms pass just over the grooved way of plate 13. If, however, the cap 17 is depressed, the bent lever 18 within it carries along the lever 16, so that the spring 19 is free to lower 15 about 0.5 cm. The grooved way of 13 is so shaped and situated that just after 5 has ceased making contact between 2 and 4 the projection at the end of 15 will now strike 13, carrying it along until 10 joins 7 with 9 when one end of 5 is just about half way between the contact pieces of 1 and 2, while the other is half way between 3 and 4 — that is, long before there is any danger of sparks jumping from 1 through 5 to 3 and charging the generator. 10 now remains held in this position until after the generator has been charged and the current has passed through the galvanometer; but as soon as 5 ceases to make connection between 1 and 3, 10 is promptly carried back so as to reëstablish the connection between 7 and 8 before the following discharge can occur, and then 15 is automatically raised and will appear presently.

The upper end of the brass bushing 20 through which the axle passes carries a horizontal flange of the shape indicated in Fig. 1*a*; and to the under sides of the arms 15 and 15′ are fastened hooked-shaped projections; so that if one of the arms happens to be over the flange it cannot be dropped, or, if previously dropped, it will be held down by the hook until the flange has been passed. This is to make sure that the arm will be dropped in time to begin properly its movement of the plate 13 and that it will not be lifted out of action until the movement has been completed. To guard against the danger of one of the hooks doing damage by striking against the flange in case it happened to be lowered just before this was

reached, the flange and the approaching sides of the hooks are beveled to sharp edges, so that the arm will be carried either below or above so as to fall as soon as the other end of the flange is reached.

To effect the automatic raising of the arm after it has re-established connection between 7 and 8, the lever 21 is provided. One end of this curves around under the flange of 20 in such a way that the hook of 15 presses it down soon after it passes well under the flange. This raises the rods 22 with their attached cross-piece, 23, which presses up one arm of the bent lever 18, pulling the other arm away from the end of the lever 16. The strong spring 24, contained in the tube which is capped by 17, now raises 16, and with it 15, as far as the hook on the under side of the latter will permit; and as soon as the flange is passed, 15 is carried up to the position shown in the figure so that it will merely pass over 13 without striking it, even though the finger continues to hold down the cap 17. When the finger is removed, a spring surrounding the tube containing the spring 24 raises the cap to the position shown, and the small flat spring 25 throws back the bent lever 18 until it is again in position for engaging the end of 16, thus automatically re-setting the instrument so that another deflection will be obtained as soon as the cap 17 is again depressed.

Depressing the cap 17′ causes the current of a single *discharging* to pass through the galvanometer by lowering 15′, which is just 90° in advance of 15.

It is advisable to make the pulley 6 heavy, so as to secure steadiness of rotation. If desirable, the rotating commutator could readily be immersed in an oil-bath.

For determining the number of times the generator is charged and discharged, any kind of rotation counter may be attached to the upper end of the axle, but for convenience one that can be thrown in or out of action at will is preferable.

BERLIN, PHYSICAL INSTITUTE OF THE UNIVERSITY,
April, 1904.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE TWENTY-FIFTH MEETING.

The Fall Meeting of the Physical Society was held in the Coliseum Building, St. Louis, Mo., on Friday, September 16, 1904.

During the forenoon the Physical Society met in joint session with Section A of the International Electrical Congress. President Webster of the American Physical Society presided.

Announcement was made by the president of the election of Professor Svante Arrhenius as an Honorary Member of the Physical Society.

The following papers were read during the joint session:

1. The State of Our Knowledge Regarding the Earth's Magnetism and Recent Remarkable Magnetic Storms. L. A. Bauer.
2. The Electric Charge of the Sun. S. Arrhenius.
3. Radioactive Change. E. Rutherford.
4. Report on Recent Developments in Electrical Theory. A. G. Webster.
5. Magneto-optics. (By title.) D. B. Brace.

During the afternoon session the following papers were read:

6. On the Nature of Thermo-electromotive Force. C. B. Thwing.
7. Concerning the Presence of Yttrium and Erbium in Fluorspar. W. J. Humphreys.
8. The Effect of Pressure upon the Light from the Electric Arc. W. J. Humphreys.
9. A Differential Galvanometer of the d'Arsonval Type. (By title.) J. C. Shedd.
10. On the Conditions which Govern the Appearance of Spark Lines in Arc Spectra. Henry Crew.
11. A Spectrophotometric Study of Solutions of Copper and Cobalt. B. E. Moore.
12. On the Chemical Combination of Certain Gases under Intense Ionization. C. W. Edwards.

Adjourned at 4 P. M.

ERNEST MERRITT,
Secretary.

On the Nature of Thermo-electromotive Force.[1]

By Charles B. Thwing.

On the hypothesis that an electric current in a metal consists of a displacement of negative corpuscles it might be expected to follow that the direction, as well as the magnitude, of the pressure tending to produce such a flow in a metallic circuit due to unequal temperatures at two points in the circuit would depend upon the rates of expansion of the metal at the two temperatures.

The coefficient of expansion of many metals, and of a number of alloys having high thermoelectric force, was determined both between 20° and 60° and between 60° and 100° with a good degree of accuracy, and the thermo-electric force of the same specimens was determined over about the same range of temperature. Comparing the rate of increase of coefficient of expansion from 40° to 80° with that of lead, the thermoelectric power of which is reckoned at null, it was found:

1. That for nickel and bismuth and for nickel alloys, having like these metals, a negative e.m.f. the rate of increase in expansion is negative and numerically larger for the metals having a high e.m.f.

2. That for metals and alloys like antimony and its alloys having a positive e.m.f. the rate of increase of expansion is positive and numerically larger for the metals having a high e.m.f.

3. That for alloys of Ni-Cu, Sb-Zn and Sb-Cd, all of which have an e.m.f. much higher than either constituent, the coefficient of expansion is abnormally low as compared with the value computed from those of the constituents, the value in the case of one of the Sb-Cd alloys being but one third the calculated value.

These results agree perfectly with the hypothesis referred to above. If the corpuscles behave in some degree like a gas under pressure the low expansion of bismuth at the hot junction would cause a pressure tending to make the corpuscles flow from hot to cold while the large value of the expansion of antimony at the hot junction would result in a diminished pressure at that point causing a flow of negative corpuscles from cold to hot. In the case of the alloys referred to above this effect would be intensified by the abnormally low expansion of these alloys, which should tend to increase the pressure upon the corpuscles when the alloy is heated.

The differences in the values of the coefficient of expansion of the metals at the two temperatures are in every case so large in comparison with the probable error of the determinations as to leave no room for doubt regarding the existence of the relation indicated.

[1]Abstract of a paper presented at the meeting of the Physical Society held at St. Louis on September 16, 1904.

Marked variation of the cofficient of expansion with the lapse of time was observed in the case of some of the metals.

CONCERNING THE PRESENCE OF YTTRIUM AND YTTERBIUM IN FLUORSPAR.[1]

BY W. J. HUMPHREYS.

MORE than one hundred samples of fluorspar from various parts of the world, America (North and South), Europe, Asia, Africa and Australia were examined by a large concave grating spectroscope. In nearly all these yttrium in widely varying amounts was detected, and in a number of them, those that contained the largest amounts of yttrium, ytterbium was also found.

Three specimens, one from Virginia, one from Texas and one from Bolivia, South America, showed the presence of decided amounts of both yttrium and ytterbium. All three of these specimens were very sensitive to temperature effects, one of them phosphorescing even on being held in the hand. A short list of unidentified solar lines probably due to these elements is given.

THE EFFECT OF PRESSURE ON THE LIGHT FROM AN ELECTRIC ARC.[2]

BY W. J. HUMPHREYS.

AN electric arc was enclosed in a steel cylinder provided with a quartz window, and the light as produced in air of high pressure examined by means of a Rowland concave grating of 21½ ft. focal length.

Thc decrease in wave frequency, detected and measured by Mohler and the author some years ago at the Johns Hopkins University, has been confirmed, and the observations with the same results have been extended to many other lines and to a somewhat higher pressure.

This work is being done through the aid of the Rumfor Fund, and apparatus is nearly ready by which the investigation can be extended to fully three hundred atmospheres pressure if necessary.

[1] Abstract of a paper presented at the meeting of the Physical Society held at St. Louis September 16, 1904.

[2] Abstract of a paper presented at the meeting of the Physical Society held at St. Louis September 16, 1904.

On the Conditions which Govern the Appearance of Spark Lines in Arc Spectra.[1]

By Henry Crew.

THE intermittent arc between magnesium electrodes was examined simultaneously with the Duddell oscillograph and the spectroscope.

1. It was found that the voltage curve of the ordinary arc thus photographed showed no extra e.m.f. at break: nor did the spectroscope show the spark line at λ 4481.

2. When the break at the arc was quickened by means of an air blast the extra e.m.f. at once appeared in the voltage curve and the spark line in the spectroscope.

3. When the arc was surrounded by an atmosphere of coal gas, thus bringing out the spark lines, the voltage curve showed the extra e.m.f. at break. This gives the probable explanation of the effect of an atmosphere of hydrogen as noted by various observers, viz., the break is quickened — hence high extra e.m.f. is introduced — hence spark lines.

4. The introduction of spark lines, by use of small currents, discovered by Hartmann, is given an interpretation different from his, but in accordance with his results, with the above results, and with the modern electron theory of the arc and spark discharge.

A Differential Galvanometer of the D'Arsonval Type.[2]

By J. C. Shedd.

THE principle of the differential galvanometer has long been known and is fully elaborated in most of the treatises on electrical measurements. As a matter of fact, however, this form of galvanometer is but little used. This is not from any lack in variety of method in using the instrument or lack of accuracy in the results obtained, but from other causes. One reason is that the amount of patience and trouble involved in successfully handling such an instrument, sensitive enough to be of any value, is often excessive. Also the necessity of having movable coils or of resorting to leveling screws for the purpose of delicate adjustment calls for a skill in manipulation beyond that possessed by the average stu-

[1] Abstract of a paper presented at the meeting of the Physical Society held at St. Louis September 16, 1904.

[2] Abstract of a paper presented at the meeting of the Physical Society held at St. Louis on September 16, 1904.

dent. In particular the dependence upon the earth's magnetic field limits the usefulness of the instrument to a few favored localities free from magnetic disturbance.

The advent of the D'Arsonval galvanometer has for most purposes relegated the fixed-coil galvanometer either to the shelf or to the advanced laboratory. The present state of perfection of this instrument has brought a galvanometer of fair sensibility and easy of manipulation within the reach of all. It has also made possible its use in localities heretofore entirely impossible, such as the dynamo laboratory, machine shop, power-station, or on ship-board.

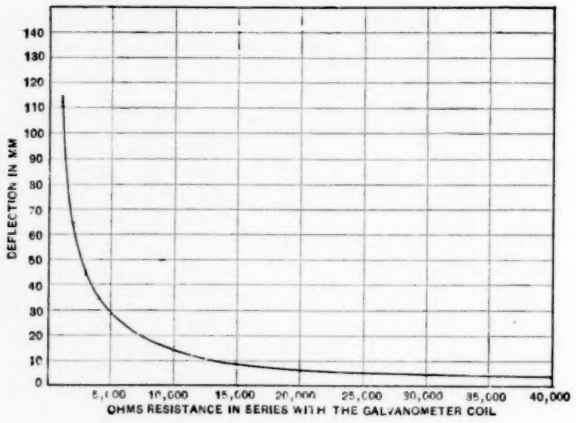

Fig. 1.

The possibility of constructing a differential galvanometer of the D'Arsonval type occurred to me some years ago but only recently has the idea taken concrete form. The work, while not complete, has progressed far enough to show that the instrument is practicable in every respect. For this purpose the coil was removed from a Rowland D'Arsonval galvanometer and a special coil substituted for it. This coil was made as follows: about 600 feet of No. 40 silk covered copper wire was measured off and then doubled back on itself. It was then run over with beeswax to render it slightly adhesive. The doubled wire was then wound by hand upon a small wooden bobbin made for the purpose, care being taken to keep the wires exactly together. The wooden bobbin was provided with two terminals insulated from each other. These were used as the terminals of one coil. To one of these terminals was fastened the upper, and to the other the lower suspension used with the original coil. The terminals of the second coil were brought out below and looped in such a manner as to reduce the tortional effect to a mini-

mum. In bringing both terminals out at the same end in the case of one coil and at opposite ends in the case of the other coil, it is apparent that one coil will have a half turn more than the other. It was thought that with something like a thousand turns on the coil this half turn would produce no appreciable effect. On trial, however, it was found that a deflection of one mm. was produced when the coils were differentially connected in series. To eliminate this the extra half turn was brought down the edge of the wooden bobbin so as to lie in the plane of the suspension wire normal to the magnetic field. Its effect was then found to be nil.

As the wire was wound on by hand some doubt was felt lest the two coils be not exactly equivalent to each other magnetically. It was therefore a satisfaction not only to find that the deflection was zero with the coils differentially connected in series but also to obtain identical calibration curves for the separate coils. This is shown in the following table the results of which are plotted in Fig. 1.

Table showing the relation between deflection and current for the two coils of the differential D' Arsonval galvanometer.

	Coil A.		Coil B.	
Resistance in Series with Coil.	Deflection in Mm.		Deflection in Mm.	
Ohms.	Direct.	Reversed.	Direct.	Reversed.
40.000	3.3	3.8	3.8	3.5
30.000	4.5	5.0	4.3	4.8
20.000	7.0	7.4	6.0	7.3
10.000	14.0	14.4	14.5	14.4
5.000	27.8	27.5	28.0	28.0
4.000	34.0	34.0	35.0	34.0
3.000	45.0	44.3	45.0	45.0
2.000	64.0	63.5	65.0	64.0
1.000	114.2	111.0	113.5	113.0

The present trial instrument is sufficient to show that the application of the differential principle to the D'Arsonval type of galvanometer is an entire success. The exact form the instrument may take may be left for the future development. It is probable that a double suspension above will be preferable to the triple suspension below. I am confident that there need be no loss of sensibility on account of the extra suspension.

The advantage of having the D'Arsonval galvanometer capable of being also used as a differential galvanometer is at once apparent and it is hoped that the use of differential methods may receive an impetus from the introduction of this form of instrument.

The following references to the literature of the Differential Galvanometer may be found of value.

On the Theory of the Instrument:

Clerk Maxwell, Electricity and Magnetism, Vol. I., pp. 472–475.

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An examination of the files of the La Lumieer Electrique and LeEclarage shows that a little work along this line was done in 1889 (III., p. 545) by M. Ledebor and M. Carpentier. Their attempt was to wind two independent coils upon the same core. This procedure must have resulted in a very cumbersome instrument. The insulation of modern wire is sufficient to allow of bifilar winding and with much better results.